TEMPERATURE VARIATIONS THROUGHOUT MONTEREY BAY, SEPTEMBER 1971-OCTOBER 1972

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THESIS

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by

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Temperature Variations Throughout Monterey Bay

September 1971-October 1972

by

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ABSTRACT

Temperature data was obtained at nine stations in Monterey Bay on a weekly basis from September 1971 to October 1972. Monthly mean depths of the isotherms were computed and compared to the long term mean depths of these isotherms. Sea surface temperature patterns and the topographies of the 10° C surface were drawn. It was found that the period from October 1971 to May 1972 was colder than normal while the months from June 1972 to October 1972 were warmer than usual. The NMFS coastal upwelling index was a relative indicator of isotherm depth in relation to the long term mean depths of these isotherms.

Quasi-synoptic observations between two offshore stations indicated that the north-south component of the offshore current seldom exceeded 20 cm/sec. The inferred flow from the surface σ_t contours and the topographies of isothermal surfaces were compared to current flow determined by drogue measurements. The overall direction of the offshore current and the inferred flow in the bay compared reasonably well to the proposed flow in the numerical model of current patterns in the bay by Garcia [1971].

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I. INTRODUCTION

A. GENERAL BACKGROUND

The Department of Oceanography of the Naval Postgraduate School (NPS) commenced a sequence of studies of the thermal structure of Monterey Bay in 1970. The first step in this project was the work done by Lammars [1971] where he computed 40-year averages of the thermal characteristics from available data and inferred currents in the bay from certain aspects of these temperatures averages. Next, Anderson [1971] compared the thermal conditions during short periods in 1966-1967 and 1970-1971 when quasi-synoptic data were available to the long term averages of Lammars. These two investigators used data collected by other researchers. In the fall of 1971 McClelland [1972] conducted a five month temperature survey of Monterey Bay using a nine station grid, visiting these stations on a weekly basis. The present author's study is a continuation of McClelland's work and provides data to complete a consecutive fourteen month study of the temperature structure of Monterey Bay.

The Monterey Bay area is one of the popular tourist attractions along the central California coast. It is a region known for its clear waters, aquatic sports and beautiful shoreline. A threat to these attractions is the growing population in the communities around the

bay. This increased population demands more and more services which are dependent to some extent on Monterey Bay. These services include disposal of waste products, the elimination of heated water from power stations and the need for oil and thus the need for ocean going tankers to provide the oil for local use. The bay has also been an important location for the commercial fishing industry.

It is important to know the temperature averages or normal thermal conditions for many reasons. For example it enables the detection of changes caused by thermal pollution. Such pollution could be caused by the introduction of relatively warm water into the bay from power plants or other industrial activities. Changes in thermal conditions could change chemical reaction rates or critically affect the environment for certain species of marine life.

One of the factors influencing the location of sewage outfalls or tanker anchorages is knowledge of what will happen to pollutants once they are deposited in the ocean. Will they be carried out to sea and be dispersed to the point where they are no longer noticed by man or harmful to marine life or will they end up concentrated in a particular area or scattered along the beaches of Monterey Bay? In order to determine which scenario will take place it is vital to understand and be able to describe the current patterns in the bay throughout the year.

It is hoped that the results of this work will be beneficial to those interested in ocean related activities where current and temperature information is necessary.

B. DESCRIPTION OF MONTEREY BAY

Monterey Bay is a nearly semi-eliptical indentation in the coastline of central California. The bay is approximately 20 miles from north to south while the depth of indentation is about 10 miles. The center of Monterey Bay is approximately 36°48'N and 121°54'W. The seaward limit of the bay is a line running from Pt. Pinos to Pt. Santa Cruz.

The bay can be divided into three main sections based on its bottom topography. These sections are the southern and northern shallows and the Monterey Submarine Canyon. The deep intrusion of the Monterey Submarine Canyon into the bay effectively splits the bay into halves. The southern shallows are south of the canyon and include that region of the bay shoreward of the 100 meters isobath. The northern shallows are north of the canyon and include that portion of the bay shoreward of the 100 meters isobath. The bottoms in these two regions of Monterey Bay are relatively flat. The Monterey Submarine Canyon has very steep sides and reaches a depth in excess of 2000 meters within 10 miles of the city of Monterey. The deepness and orientation of the canyon allows deep oceanic water access to the center of Monterey Bay.

C. PREVIOUS RESEARCH

The first long term oceanographic investigation of Monterey Bay was conducted by Skogsberg [1936]. He obtained oceanographic observations over a five year period from 1929-1933. He had 23 stations located about the bay with 21 of these in water shallower than 100 meters. The majority of these stations were in the southern portion of the bay. Due to the limited seaworthiness of his ship he was unable to visit these stations on a regular basis. Also Skogsberg was not able to visit all of the stations on a given day. In certain years only some lines of his stations were visited. Thus, while he had a long term study he did not have continuous data from a series of stations.

At his stations Skogsberg obtained temperature, salinity and other chemical data and from this information he was able to divide a year into three oceanographic seasons. These three seasons hav come to be known as the Upwelling Period, the Oceanic Period and the Davidson Current Period.

Bolin [1964] in his study of one station over the Monterey Submarine Canyon for a five year period refined the definition of the oceanographic seasons as proposed by Skogsberg as given below:

1. Upwelling Period - This period lasts from about mid-January to sometime in September. During this time the coastal water is ascending and the depth of various

isotherms become shallower. The isotherms reach their shallowest depth in April or May and begin descending in June. During this period the surface temperatures in the bay are in the 10°C to 11°C range.

2. Oceanic Period - This period commences upon the completion of the Upwelling Period when the winds become weak and intermittent. The Oceanic Period usually lasts only two months, September and October. It is generally characterized by the sea surface temperature of the bay being greater than 13°C and strong vertical temperature gradient in the upper 100 meters.

3. Davidson Current Period - This period lasts from November to mid-January, which is the period when the nearshore counter current is flowing at the surface. This period can be characterized by weak vertical temperature gradients with the surface to 50 meter region well mixed. The surface temperatures are usually lower than in the Oceanic Period but not as low as those occurring during the Upwelling Period.

These descriptions of the oceanographic seasons in Monterey Bay should be considered only as general guidelines. The periods may occur earlier or last longer than described above due to changes in the driving forces which cause them. The features of these seasons

may be more intense or hardly distinguishable depending on the generating forces during a given year.

Lammars [1971] used all available temperature data from a 40 year period to compute monthly averages of the horizontal and vertical temperature distributions in Monterey Bay. He concluded that progressive warming was occurring in the Bay and that the upper layers of the Bay over the Monterey Submarine Canyon were warmer than the shallow regions to the north and south. Lammars also concluded that the topography of the 10°C or 11°C surface (depending on the month) would be useful to infer current flow in Monterey Bay.

Anderson [1971] compared thermal conditions in Monterey Bay from September 1966 to September 1967 and from January 1970 to June 1971 to the monthly averages computed by Lammars. He compared sea surface temperature, the temperature at the 20 meter isobath and the depth of the 9°C and 10°C isotherms. He found that 1966-1967 was approximately normal but that there was more intense upwelling than normal in 1970-1971.

McClelland [1972] initiated the use of a nine station grid to cover the various regions of Monterey Bay. His study covered the Oceanic and Davidson Current Periods. He found that short term thermal fluctuations were comparable to those found by other investigators but that the seasonal changes in this period were more rapid than

previously noted. Also he computed the north-south component of the geostrophic currents between a pair of stations off Pt. Pinos.

D. OBJECTIVES

The objectives of this oceanographic study of Monterey Bay are:

1. To supplement the information obtained by McClelland [1972], obtaining temperature data for a continuous fourteen month period from a set of locations covering a substantial portion of Monterey Bay.
2. To describe the various thermal fluctuations at this set of stations in the bay and relate these fluctuations to the oceanographic seasons described by Skogsberg [1936] and Bolin [1964].
3. To compare monthly mean patterns of sea surface temperature to those based upon the 40 year monthly means computed by Lammars [1971] and attempt to explain any anomalous results.
4. To compare monthly mean topographies of the $10^{\circ}C$ surface to those based upon the 40 year monthly means determined by Lammars and attempt to explain any anomalous results.
5. To compare direct current measurements to currents inferred from some easily obtainable parameters such as the topography of a specific isothermal surface of σ_t

patterns in order to test the practicability of using such a parameter to infer currents in Monterey Bay.

6. To describe inferred currents in the fourteen month period if the above approach seems to give reasonable results.

7. To compute the geostrophic north-south components of the California or Davidson Current between two stations located off of Pt. Pinos and to compute other components between other pairs of stations located in or near Monterey Bay.

8. To relate the computed north-south components of the offshore currents to the inferred surface current patterns in the bay.

II. PROCEDURE

A. DATA COLLECTION

The majority of the data used in this study was collected from the Research Vessel ACANIA operated by the Oceanography Department of the Naval Postgraduate School. A weekly cruise was conducted which covered a nine station grid of Monterey Bay. These stations are numbered 1 through 9 in Figure 1. These nine stations were chosen to provide stations which could all be reached within a 12 to 14 hour period and yet which would provide coverage of the various features of Monterey Bay such as the southern and northern shallows, the Monterey Submarine Canyon section, and to obtain the north-south geostrophic component at two stations offshore. They were also located close to stations where previous data had been obtained by Skogsberg, Bolin and CALCOFI.

At each station a mechanical bathythermograph (MBT) was lowered to obtain the temperature profile while surface temperature was recorded using a bucket thermometer. At stations 2, 3, 4, 5 and 8 expendable bathythermographs (XBT) were also used to obtain a temperature profile. Surface temperatures were also recorded at mid-points between stations.

On most cruises Nansen casts were made at Stations 2 and 3 using 10 bottles at depths of 0, 20, 50, 100, 200, 300, 400, 600, 800

and 1000 meters. Temperatures were obtained from standard reversing thermometers while salinity was determined using an induction salinometer.

Supplementary data was obtained during several Extended Bay Cruises conducted by personnel of the Naval Postgraduate School aboard oceanographic vessels (AGOR class) provided by the Naval Oceanographic Office for short periods of time. This AGOR class of vessel enabled a greater area to be surveyed due to its overnight ability and its greater speed. The R/V ACANIA was limited at this time to daily trips due to crew limitations and had a maximum cruising speed of 10 knots.

The first Extended Bay Cruise was conducted on 8-10 May 1972. Data was obtained at the regular nine stations in the Bay Cruise plus data from the stations indicated by Roman numerals in Figure 2. The second Extended Bay Cruise was held on 16-17 May 1972 and data was collected from the nine stations of the weekly Bay Cruises plus Station II. The third Extended Bay Cruise was conducted on 1-2 August 1972 where the regular bay cruise stations were visited along with stations concerned with other oceanographic research.

Data collection procedures on these cruises were the same as on the weekly bay cruises except that when an STD was available it was used to supplement hydrographic data obtained by Nansen casts and bathythermographs.

Skogsberg [1936], McClelland [1972] and Broenkow [1972] reported the presence of internal oscillations in Monterey Bay. The oscillations occurred over a period of only hours, thus indicating non-steady conditions in the bay. Broenkow [1972] at two stations near the head of the canyon states that the oscillation of the isotherms and other oceanographic parameters was related to the tidal cycle.

It was necessary to assume that each cruise provided synoptic observations although it is obvious that large fluctuations in isotherm depth and other parameters can occur within periods of only a few hours. The time between first and last observations was 12 to 14 hours. This was the fastest coverage that could be obtained since we were limited to the use of only one vessel, the R/V ACANIA.

The weekly bay cruise data in October was supplemented by hydrographic observations made at CALCOFI station lines 67 and 70. Thus geostrophic current information was available at stations near Monterey Bay.

III. RESULTS

A. UPWELLING INDEX

The National Marine Fisheries (NMFS) and the Fleet Numerical Weather Central in Monterey calculate a coastal upwelling index for various locations along the coast of North America. The location nearest Monterey Bay is at 36°N, 122°W which is approximately 40 miles to the south of the bay. These index values are computed from the offshore component of the Ekman surface transport which is based on monthly mean surface atmospheric pressure data. Bakun [in press] has more detailed information on the procedure used to calculate the coastal upwelling index.

The annual rhythm of the upwelling cycle at 36°N 122°W is presented in Figure 3. The solid line indicates the 1971-1972 values, while the dashed line represents the long term mean values based on calculations from 1948 to 1967. From this graph, it can be seen that upwelling occurs throughout the year though it is weak during the late autumn and early winter months. The units of the upwelling index are metric tons per second per kilometer of coast.

Figure 4 shows a plot of the upwelling index anomaly. This anomaly is the difference between the monthly value of a given year and the long term mean value for the same month. A positive

anomaly means that upwelling was more intense than normal while a negative anomaly indicates the upwelling during that month was weaker than the long term mean. During the fourteen months of this oceanographic investigation, there was a positive anomaly for only 4 months. There were 2 months where the monthly upwelling index value and the long term mean were identical while there were 8 months when a negative anomaly existed.

B. THERMAL FLUCTUATIONS AT NINE BAY STATIONS

The average monthly depths of the isotherms at each of the nine stations in the Monterey Bay Cruise station grid are shown in Figures 5 through 13. The monthly average depth at a station was determined by summing the depths of the isotherms measured during a month of the weekly cruises and dividing by the number of cruises made that month at that station. The maximum depth at which temperature data was regularly obtained was 300 meters, the limiting depth of the mechanical bathythermograph. Thus at the deep water stations, Stations 2, 3, 4 and 5, the isotherm depths are shown for only the upper 300 meters. At Stations 1, 6, 7, 8 and 9 the depth capability of the bathythermograph was equal or greater than the water depth. Therefore at these stations the isotherm depths are representative of the entire water column.

In general the isotherm patterns during 1972-1973 agree with the results obtained at a few of the same locations by Skogsberg [1936]

and Bolin [1964]. Their annual cycles showed the isotherms beginning their ascent in January, reaching a peak in April or May and then descending again til January. Their patterns also show an influx of warm water during the months of August and September. Lammars [1971] has plots of the Skogsberg and Bohn annual cycles.

While the overall pattern of the isotherm fluctuations at stations where comparisons could be made was similar to previous patterns, there were several deviations from the normal. The first of these features was the apparent surge of upwelling in December 1971 and January 1972 which caused the sea surface temperature and the temperature of the upper layers at Stations 1, 2, 6, 7 and 9 to be between 10°C and 11°C, about a degree lower than normal.

Another interesting event was the warming to 12°C seen in the surface layers at Stations 3, 8 and 9 in the month of March. This occurred at the offshore station (3) and the two stations near to shore (8 and 9). The rest of the stations in the bay did not show this warming.

By far the most interesting feature was the rapid warming in the surface layers which occurred at all stations starting in June 1972. The previous works by Skogsberg and Bolin show warming beginning in June but only in the 12°C to 13°C range. In 1972 this warming caused temperatures in the 14°C to 15°C range to be present in these layers at all stations in the bay. These warm pockets in late summer

have usually disappeared by October. In October 1972 the deepest depths for the year for the 12°C - 15°C isotherms were measured indicating the greatest warming. There was obviously some heating process or weakening of upwelling taking place at this time.

Greater changes in depth of isotherms, particularly the 9°C isotherm, occurred at Stations 2, 4 and 5 than at Station 3. Stations 2, 4 and 5 are located over the Monterey Submarine Canyon, but near shore, while Station 3 is located 23 kilometers offshore. These greater changes of isotherm depth could be indicative of upwelling occurring more intensively at these coastal stations than in the offshore region.

1. Comparison of Depth of 10°C and 9°C Isotherms to 40-Year Mean Depths at Station 5

Figure 14 shows the comparison of the depths of the monthly average of the 9°C and 10°C isotherms from 1971-1972 to the 40 year mean depth as computed by Lammars [1971]. The depths of the isotherms at Station 5 are compared to the depths computed at Lammars block 3.

The depths of the 9°C and 10°C isotherms for 1971-72 correspond fairly well to the long term depths for the months of September through November 1971. From December 1971 through April 1972 the depths of the isotherms were less than the long term mean indicating that the surface layers of the bay were colder than

normal for this period. During this time the upwelling index indicated normal or stronger than normal upwelling except for the month of February. This would tend to indicate shallower depths than normal for the isotherms which is as observed.

Both the $9^{\circ}C$ and $10^{\circ}C$ isotherms reached their minimum depths in April. These depths were approximately the same as computed by Lammars but the peak in April for both isotherms occurred one month early for the $9^{\circ}C$ isotherm and two months early for the $10^{\circ}C$ isotherm.

During the period from May 1972 through October 1972, the depths of the $9^{\circ}C$ and $10^{\circ}C$ isotherms for 1971-1972 were greater than the long term mean. There was an indication that the upper layers of the bay were warmer than normal. The upwelling index for these months had a negative anomaly indicating that upwelling was not as strong as normal. Thus the combination of weak upwelling and heatir and mixing from above tended to drive the isotherms deeper.

October 1972 at Station 5 shows a rapid deepening of all isotherms indicating a period of weak upwelling. This was also the month with the largest negative anomaly of the upwelling index.

There was evidence of the same type of cycle occurring at other stations in the bay but Station 5 was used as an example because Lammars had good data from that region and it is over the canyon so there would be less influence of near-by landmass than at other stations.

Figure 15 shows the relation between the sea surface temperature (SST) for 1971-72 (solid line) at Station 5 and the long term mean determined by Lammars for his similarly located Block 3. It shows that when there was generally normal, or a positive anomaly, to the upwelling index (October 1971-April 1972) the SST was lower than normal. During the months when there was a negative anomaly to the upwelling index (May 1972-October 1972, September 1971) the SST at Station 5 was higher than the long term mean. Thus the anomaly of the upwelling index appears to be generally related to the deviation of the present sea surface temperature from the long term mean.

In Monterey Bay the upwelling index seems to be a good indicator of general trends of isotherm movement in relation to the long term means. When there is a positive anomaly indicating more intense upwelling than normal the isotherm depths were less than the long term mean. When there is a negative anomaly the isotherms were deeper than normal.

A straight line was fitted to a plot of monthly upwelling index anomaly versus the difference between the long term monthly mean depth of the 10°C isotherm and the monthly depths for 1971-1972. The slope of this line was +0.54. This plot is shown in Figure 15A.

2. Comparison of Weekly Fluctuations of the Isotherms to their Monthly Mean Values

There was rapid change in the depths of the isotherms at all stations throughout the period of this study. Figure 16 shows the

weekly fluctuations as a thin solid line and the average monthly depths are connected by the heavier line. This figure shows the fluctuations in the depth of the $10^{\circ}C$ isotherm at Station 5. It was typical of the fluctuations of other isotherms at other stations.

The weekly oscillations were generally greater than the monthly changes in the average depth of a given isotherm. On occasion these weekly changes were of the same order of magnitude as the annual change in the monthly average depths.

The change in depth of an isotherm from one week to the next could have been generated by one or several causes occurring at the same time. The temperature data could have been obtained during a different portion of the cycle of an internal wave, giving different depths at different times for the same isotherm. An eddy or a meander in the offshore current system could have been carried a different water mass into the bay, again causing the change of depths in the isotherms. The offshore current possibly switched direction between observations, again changing the characteristics of the waters of the bay.

About the only conclusion is that the waters of the bay were highly variable but that the monthly average depths of the isotherms were a reasonable indicator of the overall condition of the bay. The waters of the bay can apparently be disturbed quite easily; thus a single observation would not be indicative of mean conditions of the bay.

C. TWO STATION COMPARISON GRAPHS

Graphs of the type shown in Figures 17, 18 and 19 were used by Anderson and McClelland to portray the comparative changes with time in the sea surface temperature or depth of isotherms for a pair of stations. Each point on the graph shows the monthly average sea surface temperature or depth of an isotherm at both stations. The horizontal temperature or depth gradient can be determined if the distance between stations is known. Anderson plotted the 40 year average data compiled by Lammars for Lammars' Blocks 1, 3 and 9. Comparisons were done for Stations 4 and 8 and Stations 1 and 5 because these stations from the weekly bay cruise corresponded to Lammars' blocks. The solid line connects the average monthly values determined in 1971-1972 while the dashed line connects the 40-year monthly mean values.

From these graphs it can be seen which station changed temperature or depth most rapidly and whether or not there was a directional tendency. A positive 45 degree line implies an equal change in temperature or depth in the same direction at both stations. A more horizontal line segment indicates that the station represented along the abscissa changed more rapidly than the station represented along the ordinate.

If the monthly value of sea surface temperatures at both stations were lower than the long term mean values, then the 1971-1972

monthly value will be to the left of and lower than the long term mean value.

1. Sea Surface Temperature Comparison at Stations 1 and 5

Figure 17 compares the average monthly values of sea surface temperature at a mid-canyon station, Station 5, and a southern shallows station, Station 1. These two stations compare changes in a north-south direction. The first thing that is obvious was that there was basically two distinct periods. The first of these periods was from October 1971 through May 1972 when the sea surface temperature at both stations was lower than the 40 year means for the appropriate months. The second period consists of the months of June 1972 through October 1972 when the sea surface temperature was higher at both stations than shown by the 40-year mean values for the appropriate months.

The first period described above was also the months when there was a positive anomaly in the NMFS upwelling index. Thus it appears that when there was more intense upwelling than normal taking place, the sea surface temperature was lower than indicated by the 40-year mean value of the sea surface temperature. The second period outlined above was the months when upwelling was weaker than normal. Thus it seems that the sea surface temperature was higher than normal during these months of weak upwelling.

For all fourteen months of this study both stations were either significantly higher or lower than normal. Thus what ever was

causing changes at one station was also affecting the other station in the same manner though the magnitude of change was not the same at both stations.

Both stations were higher than normal in September 1971. The bay then rapidly cooled until December 1971 with both stations cooling at approximately the same rate. Both stations warmed slightly in January 1972 and February 1972. During March, Station 1 warmed a small amount (about 0.3°C) while Station 5 cooled slightly. Through April and May both stations again cooled. In June there was a large amount of warming at the pair of stations. This warming trend continued on through July 1972. August saw a cooling of the waters at Station 1 while the temperature remained almost constant at Station 5. In September, basically the opposite situation occurred, Station 1 remaining constant and Station 5 cooling. There was a significant warming at both stations in October 1972.

The largest change from one month to the next occurred between May and June and this happened at both stations. Thus there was a significant change in the waters at these two stations between these two months. The least monthly change at both stations took place between the months of December 1971 and January 1972 indicating that the water temperature at these two stations was relatively stable during these months.

2. Sea Surface Temperature Comparison at Stations 4 and 8

Figure 18 compares the sea surface temperature at Station 4 and Station 8, which form an east-west pair. Station 4 was located over a deep portion of the Monterey Submarine Canyon and near the open ocean while Station 8 is situated at the head of the canyon in shallower water and near the shore. Again there were two distinct periods. The first period covered the months of October 1971 through May 1972 when the sea surface temperature at both stations was lower than the sea surface temperature indicated for the appropriate months on the long term mean graph computed by Lammars. The month of April at Station 1 was the only exception to this feature. These months again are the months of average, or stronger than average upwelling. The second period consists of the months of July 1972 through October 1972. During these months the sea surface temperature at both stations was higher than normal.

The waters at Stations 4 and 8 were warmer than normal in September 1971. Both stations cooled rapidly at about the sam rate from October through December 1971. Both stations warmed slightly in January 1972 and February. In March Station 4 cooled while Station 8 warmed. Station 4 warmed at about the same rate that Station 8 cooled in April. In May both stations cooled, this possibly was due to upwelling. June showed a rapid warming at both stations and more or less a transition month between the two periods

described above. The water at both stations warmed rapidly in July. Station 4 remained approximately constant through August while Station 8 cooled slightly. September 1972 was almost identical to August at both Stations 4 and 8 indicating that no change took place in the bay at that time. October 1972 exhibited rapid warming at both stations.

The most rapid cooling at Stations 4 and 8 took place between September 1971 and October 1971. The greatest monthly increase of sea surface temperature took place between May and June at Station 4 and June and July at Station 8. The least monthly change occurred between August and September 1972 when both months were almost identical.

3. Comparison of Depths of the $9^{o}C$ Isotherm at Stations 4 and 8

Figure 19 shows the relationship between the depths of the $9^{o}C$ isotherm at Stations 4 and 8. The depths of the isotherm at both stations seems to fluctuate in a random manner from September 1971 to January 1972. Greater fluctuations in depth took place at Station 8 which is at the head of the Monterey Submarine Canyon. This could be due to the magnified surge of the internal waves at this location as described by McClelland [1972].

From January 1972 through April 1972 there was a decrease in the depth of the $9^{o}C$ isotherm at both stations. This was also the only period in 1972 when normal or more intense upwelling was

denoted by the upwelling index. These two actions correspond nicely, stronger upwelling indicating a raising of isotherms. The period from June 1972 through August 1972 showed an increase in the depth of the isotherms at both stations. This was also a period of weaker than normal upwelling as depicted by the NMFS upwelling index. Though upwelling was occurring during these months, it appears that it was not strong enough to support the isotherms against the heating and mixing occurring in the surface layers.

D. THERMAL TOPOGRAPHIC CONTOUR CHARTS

1. Sea Surface Temperature

Figures 20 through 33 show the contours of sea surface temperatures over Monterey Bay for the fourteen months that were covered in this oceanographic investigation. The isotherms were drawn at $0.2^{o}C$ intervals and relative cold regions were marked with a C while relative warm regions were marked with a W. The monthly averages were computed at each station and at each mid-point between stations using the sea surface temperatures from the weekly bay cruises. Thus, on the average, 3 or 4 weekly values were used to obtain each monthly average.

The chart from September 1971 was drawn using values obtained during the cruises of 21, 22, 23 and 28 September 1971. Thus it is probably more representative of the last 10 or 12 days of

the month than of the entire month. This chart shows a tongue of relatively cold water which more or less follows the axis of the Monterey Submarine Canyon. This band of cool water was between the warmer waters further offshore and the warm waters found near the shore.

During October the average bay temperature was generally 2°C lower than at the end of September. This relationship seemed to hold true at almost all stations, thus indicating that the bay cooled uniformly during this time. Again there was a cool band of water over the canyon axis with the region between the mid-point of Stations 1 and 2 and Station 2 being the coldest point on the bay. There was also warmer water both offshore and very near shore particularly in the southern shallows. There was a resurgence of upwelling in October which could have been the cause of the rapid uniform cooling of the bay.

From October to November the surface water of the bay cooled slightly (about 1°C), but was more uniform with 12.3°C being the most common temperature. The horizontal temperature gradients were much weaker in November than in October. There was still a large pool of cold water over the canyon but the marked increase in sea surface temperature towards the open sea and the near shore regions was absent. The general pattern present in September and October was a tongue of cool water entering the bay from the south

near Station 2. In November this tongue-like intrusion had disappeared and the isotherms took a roughly circular appearance.

The sea surface temperatures for December were lower than those for November. Again there was a roughly circular shape to the contours and a cold spot generally centered over the axis of the Monterey Submarine Canyon.

The month of January showed a slight warming over the month of December. Again there was a large pool of cool water over the canyon as in the previous month but it had expanded into the southern shallows region. The range of temperature was quite small being only 0.6°C. The chart for February shows a cold tongue of water centered at Station 6 and having a northeast-southwest trend. There is also a cold tongue centered on Station 2 and extending into the bay. The range of temperature was 0.9°C with the lowest value on the outer edge of the southern shallows and the warmest area near the shore in the southern shallows. Generally, waters were colder in the center of the bay and warmer both further offshore and very near the shore. This could be indicative of the location of upwelling occurring in the bay. Horizontal temperature gradients were generally weak.

In March the cold tongue at Station 2 had become 0.2°C colder and had spread out over the mouth of the bay. The horizontal temperature gradients were stronger because the offshore and near shore

regions had warmed while the center had been cooled. The variation between the warmest and coldest water had increased to 1.9°C. The upwelling index for March showed a marked increase in the magnitude of upwelling, thus the cool tongue is probably due to the increase of upwelling.

The April sea surface chart shows that the cold tongue from the south had pushed further into the bay causing the central part of the Monterey Submarine Canyon and region near Station 6 to be 0.2°C to 0.4°C colder than in March. The horizontal temperature gradients were weaker due to colder water being present near the shore and the extreme southern shallows.

With exception of the offshore station, Station 3, the entire bay for the month of May exhibited the lowest sea surface temperatures recorded for the period of this study. The cold tongue had intensified, being 0.6°C colder than in April. The horizontal temperature gradients were stronger. It appears from this chart that upwelling had intensified and was taking place over the canyon region of the bay or that upwelled water was moving in from the south. There was a warm tongue pushing out from the head of the canyon near Station 8 which could possibly have been due to warm river runoff. There were again low temperatures in the center of the bay with high temperatures near shore and offshore.

The June chart shows a very different pattern than that shown in May. Instead of the usual cold tongue from the south, there is a very warm tongue pushing into the bay from the south. In general the sea surface temperatures for June are 2 or 3 degrees warmer than in May. There appears to have been a cold region located in the northern shallows and in the southern shallows near Station 9. From this chart it appears that upwelling was no longer dominating the bay and that some other feature had taken over. This was anomalous to the upwelling index which showed the strongest upwelling of the year though it was less than the long term average.

July showed a general warming for the bay over the previous month. There was a relative cold region located between Stations 2 and 3 which pushed its way into the southern shallows. There was a large increase in temperature as one moved shoreward of Station 2 with a warm region generated in the extreme southern shallows. There was a very strong horizontal temperature gradient in these areas. Possibly the upwelled water had been pushed to the southwest.

The monthly averages for August were slightly lower than the July values. There was a pool of cool water located in the vicinity of Stations 2 and 4. From this region there was a strong increase in sea surface temperature as one moved shoreward. There was a strange feature at Station 5 where there was an intrusion of a warm tongue of water. There was a strong horizontal temperature gradient present in the bay during August.

The region of cold water present in August had contracted by September but did not significantly change temperature. The offshore waters had warmed while the near shore waters had cooled. The warm intrusion at Station 5 which appeared in August had disappeared by September. The horizontal temperature gradients were weaker than in August, particularly in the southern shallows.

October was a very anomalous month. It is usually cooler than August but this particular month the sea surface temperatures were much higher. There was a cold region with its center in the southern shallows which expanded out over the Monterey Submarine Canyon. An interesting feature is that the southern shallows remained at the same temperature as in September. Thus the greatest increase in sea surface temperature occurred over the canyon and in the offshore areas. The relative cold tongue in October was a relative warm region in September. There was also a warm area entering the Monterey Bay region between Stations 2 and 3.

Generally there was a cool region over the Monterey Submarine Canyon with the waters becoming warmer offshore and near the shore.

The two months that overlapped in this study were September and October. A comparison of the sea surface temperature for September 1971 and 1972 showed that the bay was warmer in 1971 by about $1^{\circ}C$. The general trend of the contours was the same with

a region of cool water over the axis of the canyon and warmer water at Station 3 and in the southern shallows. A comparison of the October 1971 and 1972 charts showed that 1972 was approximately 2.0°C warmer than 1971. October 1971 showed a region of cool water over the axis of the canyon with the general direction of the isotherms oriented north-south. The chart for 1972 shows a region of cool water over the canyon and the southern shallows with the isotherms generally running east-west.

This brief comparison showed that the same two months a year apart are very different from each other. This difference was shown in the sea surface temperatures and in the general orientation of the temperature contours.

2. <u>Mean Topography of 10°C Isothermal Surface</u>

The topography of the 10°C isotherm was chosen because it probably best described the characteristics of the mid-waters (40-100 meters). The mid-waters were selected because it is at these depths that the largest changes occur. This isotherm was also observed at most stations during the fourteen months of this study. The mean topographies of the 10°C isothermal surfaces for the months of September 1971 through October 1972 are plotted in Figure 34 through 47. The larger number indicates a greater depth of the isotherm and the contours are drawn in 10 meter intervals. A "W" indicates an area where the depth of the isotherm was deeper in

relation to the rest of the region and thus there was a thicker layer of warm water above this depth. A "C" indicates a region where the isotherm was closer to the surface in relation to other areas and thus an area where the layer of warm water above this point was thinner.

September 1971 exhibited a cold core of water located at the mid-point between Stations 2 and 3. The 10°C isotherm was very near the surface during this month at this point. The range of depths for this isotherm for September was 95 meters.

October 1971 shows a warm intrusion over the canyon from both directions, the ocean side and the head of the canyon. The northern and southern shallows were regions of cold. It appears the cold water in the canyon flowed up the sides of the canyon and seeped along or near the bottom to the shallow regions. The range of depths recorded in October for the 10°C isotherm was 82 meters.

November 1971 again shows the depth of the 10°C isotherm to be greater over the canyon than over the shallow portions of the bay. This would again indicate a flowing of water up and over the sides of the canyon and into the shallow regions. The range of depths of the 10°C isotherm was about 100 meters.

December 1971 also had greater depths for the 10°C isotherm over the canyon than in shallow regions. There was an anomalous cold spot between Stations 2 and 3 which could have been a small localized region of upwelled water. The range in this month was 75 meters for the isotherm.

January 1972 still had warmer water over the canyon to greater depths than over the shallow sections of the bay. The small localized shallow portion of the $10^{\circ}C$ isotherm between Stations 2 and 3 was again evident in January. The range of the depths for the $10^{\circ}C$ isotherm was 73 meters.

February 1972 had a warm water mass over the canyon with depth of the $10^{\circ}C$ isotherm becoming shallower as one came nearer to the shore. The range of the depths recorded for the $10^{\circ}C$ isotherm in February was 53 meters. This was a considerably smaller range than previously recorded and could have been due to the onset of upwelling. The upwelling would tend to decrease the depth of the $10^{\circ}C$ isotherm particularly over the canyon where upwelling was strongest and this would tend to decrease the range of recorded depths.

March 1972 showed a general decrease in depth of the isotherm from Station 3 towards the coastline. The range of depths was 62 meters.

April 1972 had the least interesting of the monthly patterns. The isotherm was slightly deeper offshore than over the inner portion of the bay. The range was considerably smaller than previously recorded, being only 34 meters. This was the month that the isotherms reached their shallowest depth and the depth in deep water was about the same as in shallow water. Thus there was no indication

of the seeping of water of this temperature up the sides of the canyon and into the shallow regions of the bay.

May again has a warm layer indicated over the Monterey Submarine Canyon. The range of depths was small, 33 meters, this being a month of strong upwelling.

June 1971 was a month with a weak data base. The topography of the 10°C isotherm shows a warm region over the canyon. The range of depths was 40 meters, slightly larger than April and May but still relatively uniform throughout the bay.

July was an uninteresting month and again there was only a small change, 30 meters, in the depth of the 10°C isotherm during this month of still strong upwelling.

August had a warm tongue over the canyon with the depth of the 10°C isotherm becoming shallower in the shallow portions of Monterey Bay. The range of depths was again minimal, 30 meters.

September 1972 had a warm patch of water located at Station 5 over the axis of the Monterey Submarine Canyon. The depth of the isotherm rapidly lessens in the shallower portions of the bay. The upwelling index shows a marked drop in the intensity of upwelling for September and there was a significant change in the range of the depth of the 10°C isotherm, being 70 meters for this month.

October 1972 shows a reverse pattern than had been seen in previous months. The greatest depth of the 10°C isotherm

occurred at Station 8 at the head of the canyon with the depth of the isotherm becoming shallower further seaward along the axis of the canyon. This was again a month of weak upwelling and the range of depths recorded for the isotherm was about 70 meters.

During the months of relatively weak upwelling, September through March, there were strong horizontal and vertical gradients of the depth of the 10°C isotherm. The depths were greatest over the canyon and closest to the surface in the northern and southern shallows regions. This could have possibly been due to the water flowing up the sides of the canyon and then seeping along or near the bottom into the shallow regions. The range of the depths recorded during this period was 70 to 100 meters in a given month.

The months of April through August were months of relatively strong upwelling and during these months there was only a weak horizontal and vertical gradient of the depth of the 10°C isotherm. A commonly monthly range during these months was about 30 meters

Generally there was a warm layer of water located over the axis of the Monterey Submarine Canyon. The depth to the 10°C isotherm decreased as the depth became shallower.

E. CURRENT PATTERNS IN MONTEREY BAY

An objective of this study was to attempt to find an easily obtainable parameter which could be used to describe the general surface current patterns in Monterey Bay. In order to check the usefulness

of the various selected parameters, the results obtained from them were compared to direct current measurements. Parachute drogues were used to determine directly the current speed and direction during a portion of the oceanographic investigation of Monterey Bay prepared for the Association of Monterey Bay Area Governments (AMBAG) by Oceanographic Services, Inc. In a few selected situations, these drogue studies provided the type of direct current measurements desired.

Four drogue studies were conducted between June 1972 and August 1972 and the paths of the drogues are shown in Figures 48 through 51. These studies consisted of placing a number of parachute drogues in a line generally running north-south and then tracking them over approximately 24 hours. The drogues were rigged so that the parachutes would deploy at a depth of 10 meters. With the parachutes at this shallow depth, the drogue movements were probably indicative of the surface currents in the bay. These drogues were either tracked from a radar system located at the Naval Postgraduate School according to the procedures outlined by Stoddard [1971] or they were tracked using a ship and standard navigational procedures.

1. Relation of currents to Isothermal Surfaces

Leipper [1970] showed that temperature data alone could be used to approximate the major currents in the Gulf of Mexico when there were few direct current measurements available and there was

insufficient data for the geostrophic computations. Data collected on several cruises there during the period 1965-1966 were compiled to plot topographies of the 22°C isothermal surface. It was found that, as would be expected under the geostrophic assumptions, the current generally followed the contours with the greater depths of the isothermal surface being on the right-hand side of the current as the observer faces downstream.

Lammars [1971] investigated the feasibility of relating mean currents in Monterey Bay to mean isothermal surfaces in a manner similar to that employed by Leipper. Lammars used the topographies of the 10°C or 11°C surface in his investigation because he believed that these surfaces provided the mean isothermal surfaces most likely to be related to changes in the mean current. At a few times when observations were available, he compared direct current measurements taken on a given day in a given month to the topography of the 40-year mean of the appropriate isothermal surface for that month. He found a general agreement between the inferred flow and the few available direct measurements of the currents.

It was hoped that currents could be inferred as outlined above from the data obtained during the weekly bay cruises conducted for the present study of Monterey Bay. When the currents inferred from the topographies of various isothermal surfaces were compared to the few available drogue paths it was found that there seemed to be no

good correlation. An example of this was the comparison of inferred currents to drogues tracked on 20-21 June 1972.

Figures 52 through 54 show the topographies of various isothermal surfaces and the drogue tracks for 20-21 June 1972 and 30-31 August 1972. The isothermal surfaces are plotted in 10 meter intervals. The drogues are numbered and the initial position of each drogue is marked with an S while the final position recorded for each drogue is marked with an E. The various topographies plotted were the monthly means for the $9^{\circ}C$, $10^{\circ}C$, $11^{\circ}C$ and $12^{\circ}C$ isothermal surfaces and the values for these same isotherms on a few selected single days. When these drogue paths were compared to the inferred currents as determined by the 40-year mean isothermal surfaces computed by Lammars, there was again no good correlation between inferred current paths and direct current paths.

The drogue paths were also compared to the sea surface temperature contours, both monthly averages and those obtained the day nearest to the day of the drogue study. There was good correlation between drogue tracks and sea surface temperature contours for the drogue study of 20-21 June. Figure 55 shows that drogues numbered 2 through 6 had moved in the same direction as the current inferred from the temperature contours. There was excellent correlation between the drogues paths of 30-31 August and the mean monthly sea surface temperature contours for both August and September. This is shown in Figures 56 and 57.

As can be seen in these few cases, the best correlation was between the flow inferred from the SST pattern and the direct measurement of the current. The drogues show a current which is going to the east or northeast. When mid-depth isotherms were used the inferred flow shows the current with a generally southerly flow or to the southwest. The comparison of flow inferred from mid-depth isotherms to that measured directly by drogues in June, July and August 1972 showed no correlation.

One reason why the mid-depth isotherm approach may not always be used is that, because of large salinity variations, the topography of an isothermal surface may not be an indicator of the density structure upon which this method is predicated. Another reason why this approach may fail at times is that the flow may not be always geostrophic. These Monterey Bay surface currents are generally weak and could be easily perturbed by local winds, bottom topography or tidal forces. Also, sudden changes may possibly be brought about by changes in offshore meanders or eddies.

2. Relation of Drogue Tracks to Surface Sigma-T Contours

The next parameter to be investigated was the surface value of σ_t. The salinity data used in this study was obtained from Moss Landing Marine Laboratory (MLML) and Hopkins Marine Station (HMS). This data was particularly appropriate since it was collected on the same day or within one or two days of the AMBAG drogue studies.

Figure 58 shows the location of stations where surface σ_t values were available. All stations were not visited on the same day but were sampled on consecutive days. Moss Landing's stations are marked with an open circle while Hopkins' stations are located with a cross. Contours of surface values were plotted using an interval of 0.1 units. Drogue tracks are marked as before.

The comparison of surface σ_t values to the drogue tracks is shown in Figures 59 and 60. The direction of the flow of the inferred current would have the higher value of σ_t on the observers left-hand side when facing downstream. This is assuming that the flow is geostrophic and that surface is indicative of density distribution. The flow as inferred from the σ_t values and the flow indicated by the drogues are generally in the same direction, both show flow to the northeast.

Figure 60 shows the drogue tracks and surface contours for 30-31 August. This study is particularly useful because there are drogue tracks in both the northern and southern shallows of Monterey Bay. There is excellent agreement between the current as indicated by the drogues and the current as inferred from the surface σ_t values. Both currents show flow entering the bay in the southern shallows and leaving the bay in the northern shallows.

The results obtained by comparing direct current measurements to current flow inferred from contours of surface σ_t are

encouraging and tend to support the use of such an inference at times to obtain the general direction of surface currents in Monterey Bay.

F. OFFSHORE CURRENTS

1. General Comments on the Offshore Current

An objective of this research was to examine the north-south component of the geostrophic current near the southern entrance of Monterey Bay. The majority of the data was obtained at Stations 2 and 3 from the weekly Monterey Bay cruises. Data was collected at these stations by means of Nansen casts to 1000 meters during the weekly cruises while a self-contained STD was used during the Extended Bay Cruises. Data at Extended Bay cruise stations III and II were available for May 1972. Another series of cruises was conducted in October 1972 using an STD system to record temperature, salinity and depth at the Bay Stations and some CALCOFI Stations which were in or near Monterey Bay. These casts only went to a depth of 600 meters. All pairs of stations where offshore current data was avail able can be seen in Figure 61.

The initial plan for this study involved the use of an STD so that salinity, temperature and depth data would be available on a weekly basis for all stations in the bay. This would have given the density structure of Monterey and from this it was hoped that geostrophic currents could be inferred. However, the STD was lost

at sea during one of the extended Bay cruises. Funds were not available to replace this expensive instrument and thus most of the data obtained during the year was temperature data only.

The Naval Postgraduate School IBM 360 computer system was then used with a modified NPS Department of Oceanography geostrophic program to process the data. This program made the dynamic calculations necessary to give the geostrophic current velocities at standard depths using a reference level of 1000 meters. When the cast depth was less than 1000 meters at either station or both stations, the computer was programmed to use the deepest standard depth reached at both stations as the reference level. The program also plots a profile of the current velocity components and provides mass transport data.

The north-south current velocity components observed at Stations II and III are plotted as a function of depth in Figures 62 through 64. Portions of the curves appearing to the right of the ordinate indicate a northward flowing current. Depths are in meters, and velocities are in centimeters per second.

2. Synopsis of California Current

The California Current is a southeastward flowing current located off the west coast of North America. Wooster and Reid [1963] indicate that the California Current is the eastern boundary current in the clockwise circulation pattern of the North Pacific Ocean.

This current extends approximately 500 miles from the coastline and flows at speeds generally less than 0.5 knot. Since it is an extension of the Aleutian Current, it carries the cold waters of the Gulf of Alaska to the south. This water is warmed as it proceeds to the south due to the effects of mixing with warmer waters and the effects of solar insolation according to Reid, Roden and Wylie [1958].

Jennings and Schwartzlose [1960] used drogues with the parachutes set at 10 meters to investigate the California Current in March 1958. They found that the current was flowing to the southeast with an approximate speed of 0.5 knot. Crowe and Schwartzlose [1972] have shown that drift bottles released to the north of Monterey Bay during the summer months will drift into Monterey Bay or to the coastline south of the bay, thus indicating a southerly flow off the central California coast during these months.

3. <u>Synopsis of Davidson Current</u>

The Davidson Current is the name given to the northward flowing countercurrent which is inshore of the California Current. Sverdrup, Johnson and Fleming [1942] state that this countercurrent is present throughout the year at a depth below 200 meters and that it becomes a surface feature only in the late fall and winter when upwelling has ceased. Anderson [1971] has brief descriptions of the various proposed theories as to why the Davidson Current exists.

Reid [1962] used parachute drogues to measure the flow at 250 meters in the Davidson Current during November 1961. He found a northward flow in a 40 mile wide section near the coast with a maximum speed of about 0.5 knot. Crowe and Schwartzlose [1972] in their compilation of 10 years of drift bottle data show that only those bottles released near the coast are recovered. This would correspond to Reid's observation that the Davidson Current is narrow and inshore of the California Current. Reid and Schwartzlose [1962] used both parachute drogues and geostrophic calculations to measure the Davidson Current and found that the two methods compared favorably.

4. Variations in the Flow of the Offshore Currents

The California and Davidson Currents are generally weak currents with their maximum speed less than 0.5 knot. Since these current systems are weak, they are easily perturbed and the overall trend of the currents near the coast may be masked by stronger but short term currents induced by outside forces such as strong local winds, eddies or meanders in the current system, or tidal influence.

Eddy flow may be the main feature at work which masks the overall current movement. Reid, Roden and Wylie [1958] state that some disturbances in current flow are found on the inshore side of the current. Evidence of eddy flow has been seen in a number of past studies. Reid [1962] found eddy motion in his drogue study of the Davidson Current off the coast of central California in 1961. His

offshore drogues showed a clockwise eddy present with a portion of the drogues greater than 40 miles offshore going to the south while some even further seaward were tracked moving to the north.

The 1950-1964 mean monthly charts of the geostrophic flow at the surface and 200 meters as presented in CALCOFI Atlas Number 4 show an eddy to be present during most months near the central California coast and Monterey Bay. These eddies were present either when the California or Davidson Current was the predominate current system off the mouth of the bay.

The flow in the offshore current has some effect on the waters of Monterey Bay. This was shown in the results of drift bottle studies conducted by CALCOFI from 1955 to 1971 and presented in CALCOFI Atlas Number 16. This report revealed that drift bottles released near shore and north of Monterey Bay end up on the beaches surrounding the bay when the California Current was the dominate current. Bottles released near shore and south of Monterey Bay during the Davidson Current period also end up on the shores of the bay. These offshore currents apparently transfer the drift bottles to the current patterns in the bay.

5. <u>Current Profiles and Mass Transport for Stations 2 and 3</u>

There were 42 cruises during the fourteen months of this oceanographic investigation for which the north-south component of the geostrophic current and mass transport were computed. The

individual profiles are shown in Figures 62 through 64 while a graph of mass transport is shown in Figure 62A.

The mass transport graph shows the direction of the overall flow from a given profile. An individual profile may have two or three current layers but the mass transport will present the direction of the net flow.

From the months of September 1971 through May 1972, seventeen measurements of the mass transport indicated a northward flow while nine measurements depicted a southward flow between these two stations. It appears that the Davidson Current in this observed period commenced two months earlier than normal and possibly lasted four months longer than its normal cut-off month of January. The direction of the current seemed to change directions every few weeks and maintained the new direction for several weeks. The period from June 1972 through October 1972 showed a very dominant southerly flow.

The current profiles generally showed that the maximum current velocity was found in the upper 100 meters and that the maximum speed was usually less than 20 centimeters per second though there were several instances where the maximum current speed was as much as 40 centimeters per second.

There were several interesting features noted in some of the current profiles. There was a large acceleration in current flow

between the data collected on 8 and 9 May 1972. This rapid change could have been caused by an intensification of local winds or a movement of the faster offshore current shoreward. The current had changed direction by 16 May. There was a marked decrease in the current speed between 16 and 17 May. This change could have been caused by strong northerly winds offsetting the flow of the northward flowing current of the passage of an eddy.

During the cruise of 17 August a special stop was made at the mid-point between Stations 2 and 3 and a Nansen cast was taken. The current between Stations 2 and 2 showed a predominantly southward flow with its maximum speed of 7 centimeters per second at 250 meters. The current profile between Stations 2 and 3 indicated a northward flowing current with a maximum speed of 27 centimeters per second found at the surface. The normal current profile for Stations 2 and 3 had a northerly current from the surface to about 250 meters with its maximum speed of 15 centimeters per second a the surface. Below 250 meters there was a very weak southerly flow. These three profiles can be seen in Figure 65.

The north-south components of the geostrophic current computed from 24 August to 14 October indicated relatively strong southward flowing currents. A distinctive feature of this period was a pulsating rhythm. One week the current is relatively fast and the next week it had slowed down considerably and the following week

its speed had increased again. Also from 29 August through 21 September there was a core of high current speed at a depth of 100 to 150 meters. On 2 October 1972 and 14 October 1972 this core of high current had shifted to a depth of 200 to 250 meters.

6. Current Profiles from Other Stations in and near Monterey Bay

A limited amount of data was available to compute the north-south component of the offshore geostrophic current. This data was available for Stations II and III of the Extended Bay Cruise of 8-10 May 1972 and at CALCOFI Stations 67-50, 67-55, and 67-60 and Stations 70-55 and 70-60 for two cruises in October 1972. Since this data was of such a limited nature it was not useful in this work but is presented in Figure 66 for future work.

7. Relation of Offshore Current to Current Patterns in Monterey Bay

Garcia [1971] developed a numerical model of the current patterns in Monterey Bay. He found that a closed gyre could be established in the bay. In order to determine the validity of such a model it is necessary to check it against field measurements of the currents. In paragraph III-E-2 it was shown that there was reasonable correlation between drogue paths and the current direction inferred from surface sigma-t values. Assuming that surface sigma-t contours can be used in all months to infer current patterns, it

would be interesting to compare the currents inferred from these contours to the current patterns predicted by the numerical model

Current flow in the bay in the model depends on the direction of the offshore current. The offshore current drives the bay currents by means of a shear stress mechanism. A southward flowing offshore current would cause a counterclockwise gyre while a northward flowing offshore current would cause a clockwise gyre.

Figures 67 through 78 show the inferred currents based on the available surface sigma-t contours. The geostrophic current profile computed between Stations 2 and 3 is shown on the left-hand side of the figure. There were twelve periods when data was available to plot contours of surface sigma-t and nine periods when the data of the computation of the offshore geostrophic current was close to date when sigma-t data was collected.

For eight of the twelve periods the relationship between the direction of the offshore current and the inferred current flow in the bay were in agreement with Garcia's model. The months of December 1971 and June 1972 could not be compared because the difference in time of the two data collection period. November 1972 was not compared because no general trend could be found in the current patterns in the bay. The month of March 1972 was the only month when the direction of flow in the gyre predicted by the model and the

inferred flow did not correspond. This could have possibly been caused by a meander of the offshore current system bending into Monterey Bay.

It appears that the direction of the gyre in the bay predicted by Garcia's numerical model conforms to the general trend of flow as inferred from surface sigma-t contours. This tentative conclusion is based only on a rather small number of cases and further investigation of this relationship should be conducted.

G. TEMPERATURE - SALINITY RELATIONSHIPS AT STATIONS 2 AND 3

The temperature - salinity curves shown in Figures 80 through 94 were typical curves selected from each month of the study. They were drawn from Nansen cast data obtained at Stations 2 and 3 during the weekly bay cruises. The solid line represents the temperature - salinity curve for Station 2 while the dashed line depicts the curve for Station 3.

Figure 78 shows the monthly curves for Station 2 and Figure 79 shows the monthly curves for Station 2. These monthly curves were drawn from the temperature - salinity curves described above. There was a wide variation in the characteristics of the upper layers of these waters (less than 200 meters) at both stations but the deeper layers were generally consistent throughout the fourteen months. The waters in the lower layers (greater than 200 meters) were

classified as North Pacific Intermediate Waters. Station 3 showed more variability than Station 3 in these deeper waters. This was probably because this outer station was affected to a greater degree by the variations in the California and Davidson Currents.

There seemed to be several distinct periods in the temperature - salinity relationship of surface waters at Stations 2 and 3. The September 1971 and October 1971 curves were probably the remnants of the summer season of 1971. The months of November 1971 through January 1971 showed a decrease in temperature but maintained the same salinity as present in earlier months. The months of February 1972 through April 1972 maintained the same surface temperatures as the previous three months, but there was a 0.3 to 0.4 parts per thousand decrease in the surface salinities. May exhibited the lowest temperatures in the upper layers and a marked increase in the surface salinities from the earlier months. Both of these features were most likely caused by the cold and more saline waters at greater depths being lifted to the surface by the upwelling process. June appeared to be a transition month from the cold, low saline months of November 1971 through May 1972 to the warm, high salinity months from July 1972 through October 1972. This last group of months showed an increase in surface temperatures of up to $4^{o}C$ over the previous months. The salinities of this last period were lower than those observed in May but higher than those obtained during February, March and April.

IV. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

The coastal upwelling index computed for 36°N, 122°W by the National Marine Fisheries Service and Fleet Numerical Weather Center was found to be a reasonable indicator of the isotherm depths and sea surface temperatures in Monterey Bay in relation to the long term isotherm depths and sea surface temperatures computed by Lammars for the fourteen months (September 1971-October 1972) included in this study. During the months when upwelling was more intense than denoted by the 20 year mean value of the index, the isotherms were shallower and the sea surface temperatures were lower than normal. During the months when the coastal upwelling index indicated weaker than normal upwelling, the isotherms were found at greater depths and the sea surface temperatures were warmer than depicted by the long term mean values.

There seemed to have been several anomalous features in the 1971-72 oceanographic seasons when compared to those described by Skogsberg and Bolin. The Davidson Current apparently commenced as early as October 1971, about one month ahead of its usual starting date. It also appears to have lasted about four months longer than normal, ceasing its flow in May instead of January.

Thus the Davidson Current was present during the first portion of the usual Upwelling Period. During this study, the minimum depths of the isotherms were obtained one to two months earlier than in the description of the Upwelling Period as given by Skogsberg and Bolin. The Oceanic Period, which is normally only present in September and October, appears in 1972 to have commenced at the end of June or early July and lasted only through October. Thus, the oceanographic seasons as described by Skogsberg and Bolin occurred earlier and lasted longer in the time span of fourteen months covered in this study.

The monthly mean patterns of sea surface temperature usually had a relative cold area located over the axis of the Monterey Submarine Canyon and the outer edge of the southern shallows. It could not be determined if this cool region was caused by the presence of water upwelled in this location or whether it had been advected into the region.

The monthly mean topographies of the $10^{\circ}C$ surface indicated that there was generally a thicker layer of warm water located over the canyon axis which was generally consistent with the long term means. During months of strong upwelling the $10^{\circ}C$ topography showed weak horizontal and vertical gradients. The months of weak upwelling showed strong gradients in both the horizontal and vertical directions. It appeared that during these weak upwelling months that

the cold water flowed up the sides of the Monterey Submarine Canyon and seeped into the shallow regions of the bay at or near the bay floor.

It was found for the few parachute drogue studies available that the contours of surface sigma-t values were reasonable indicators of the current flow as described by the drogue paths. The monthly mean sea surface temperature contours for June 1972 and August and September 1972 were also good indicators of the general flow of the current as denoted by the drogue paths of 20-21 June 1972 and 30-31 August 1972. The topographies of various isothermal surfaces, both monthly mean surfaces and those obtained the day of the drogue studies, were not reliable indicators of the current as described by the drogue paths. It was thought that these surfaces would be related to the mean density structure of the bay and thus would be indicators of the general mean flow in the bay. Strong geostrophic flow would not be expected during these summer months due to the weak horizontal gradients of the isotherm so that good correlation with direct currents would not necessarily be expected.

The large number of north-south geostrophic current profiles computed between Stations 2 and 3 showed that the maximum current speed was usually less than 20 centimeters per second and that this maximum speed occurred at the surface or in the upper 100 meters. The overall direction of the geostrophic current was toward the north

from September 1971 through May 1972. From June 1972 through October 1972 the general direction of the current between Stations 2 and 3 was to the south.

A comparison between the current flow indicated by the available sigma-t contours and the flow predicted by Garcia's [1971] numerical model of current patterns in the bay was conducted. It was found that there was good agreement between the overall current flow between Stations 2 and 3 and the current flow in the bay. Thus it appears from this limited investigation that Garcia's numerical model current pattern are indicative of flow in the bay.

The temperature - salinity curves for Stations 2 and 3 showed several periods when the surface waters at these stations had the same characteristics. The period from November 1971 through April 1972 showed cold-low salinity water to have been present at these stations. In the months from June 1972 to October 1972 the surface waters were warmer and more saline than in the previous period. The curves for all months at both stations were nearly the same for the deeper layers and this water was classified as North Pacific Intermediate Water.

A comparison of the current flow between Stations 2 and 3 and the current flow in the bay was conducted. It was found that the relationship between the direction of the overall offshore flow and the flow within Monterey Bay was the same as predicted by Garcia's

numerical model. This was done for only a few days when data was available. This should be used with caution but the preliminary results were encouraging.

The one overall description of the waters of Monterey Bay that is appropriate at all times is that these waters are extremely variable. Evidence of this variability was shown in the large weekly fluctuations of the depths of isotherms at all stations in the bay, the various oceanographic seasons occurring earlier and lasting longer than described in past investigations and the change in the characteristics of the surface waters at Stations 2 and 3 on a monthly basis.

B. RECOMMENDATIONS

It is recommended that the bay cruises be continued on a weekly basis. The data base for Monterey Bay could be greatly improved if the Naval Postgraduate School, Moss Landing Marine Laboratory and Hopkins Marine Station coordinated their weekly and monthly cruise schedules so that the respective cruises would take place on the same day. This would increase the amount of synoptic data and events occurring in the bay could be described.

In order to increase the usefulness of the data from the weekly bay cruises, it is recommended that a new station be established at least 22 kilometers directly north of Station 3 and that a Nansen or STD cast be conducted there and that surface salinity samples be

collected at all stations. The new station would allow for the computation of the east-west component of the geostrophic current while the surface salinities would permit the calculation of surface sigma-t values so that the use of this parameter can be further investigated in determining surface current patterns in Monterey Bay.

It is also recommended that at least a year-long series of direct current measurements be taken in order to obtain a better understanding of current patterns in Monterey Bay.

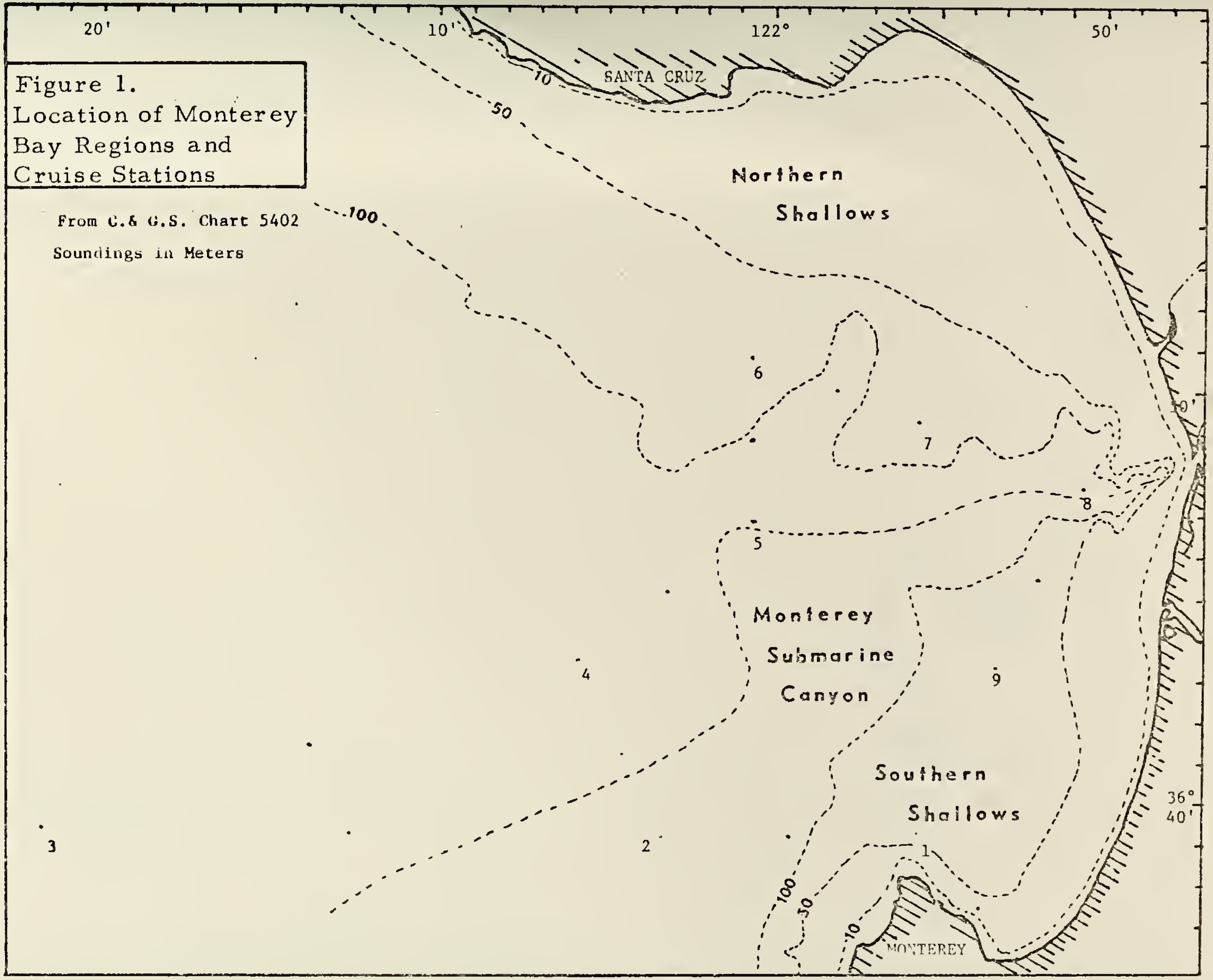


Figure 1.
Location of Monterey Bay Regions and Cruise Stations

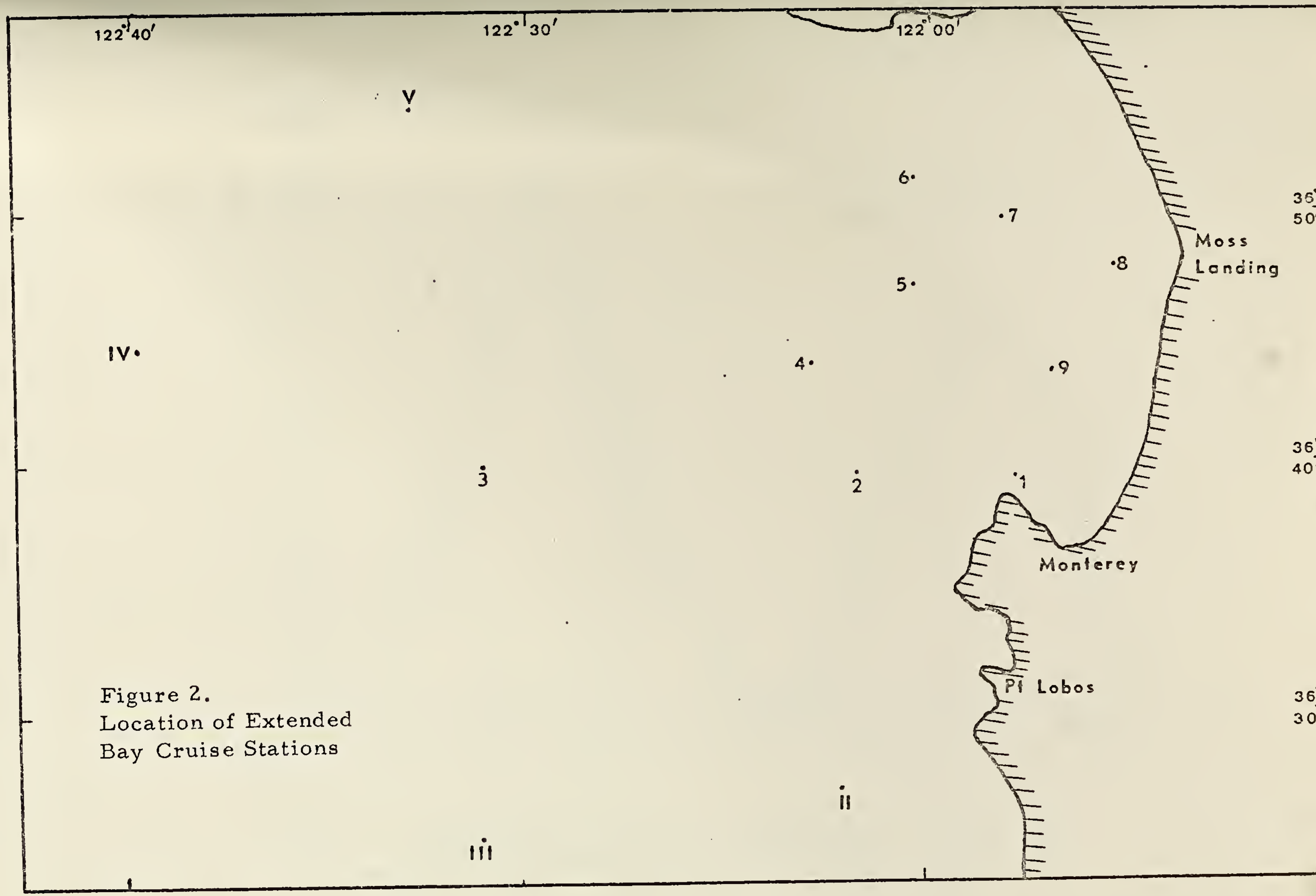


Figure 2.
Location of Extended
Bay Cruise Stations

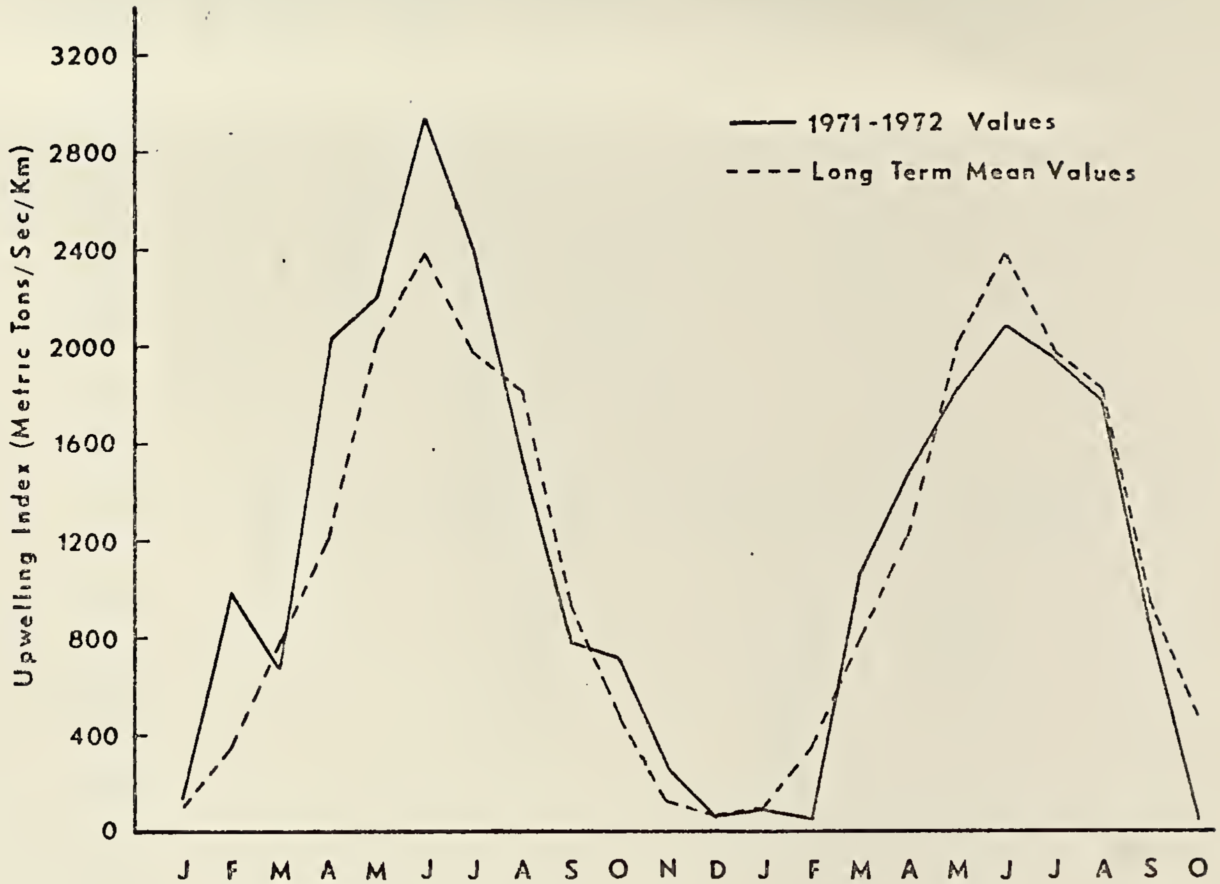


Figure 3. Comparison of 1971-1972 Monthly Value of Upwelling Index to the Long Term Mean Values

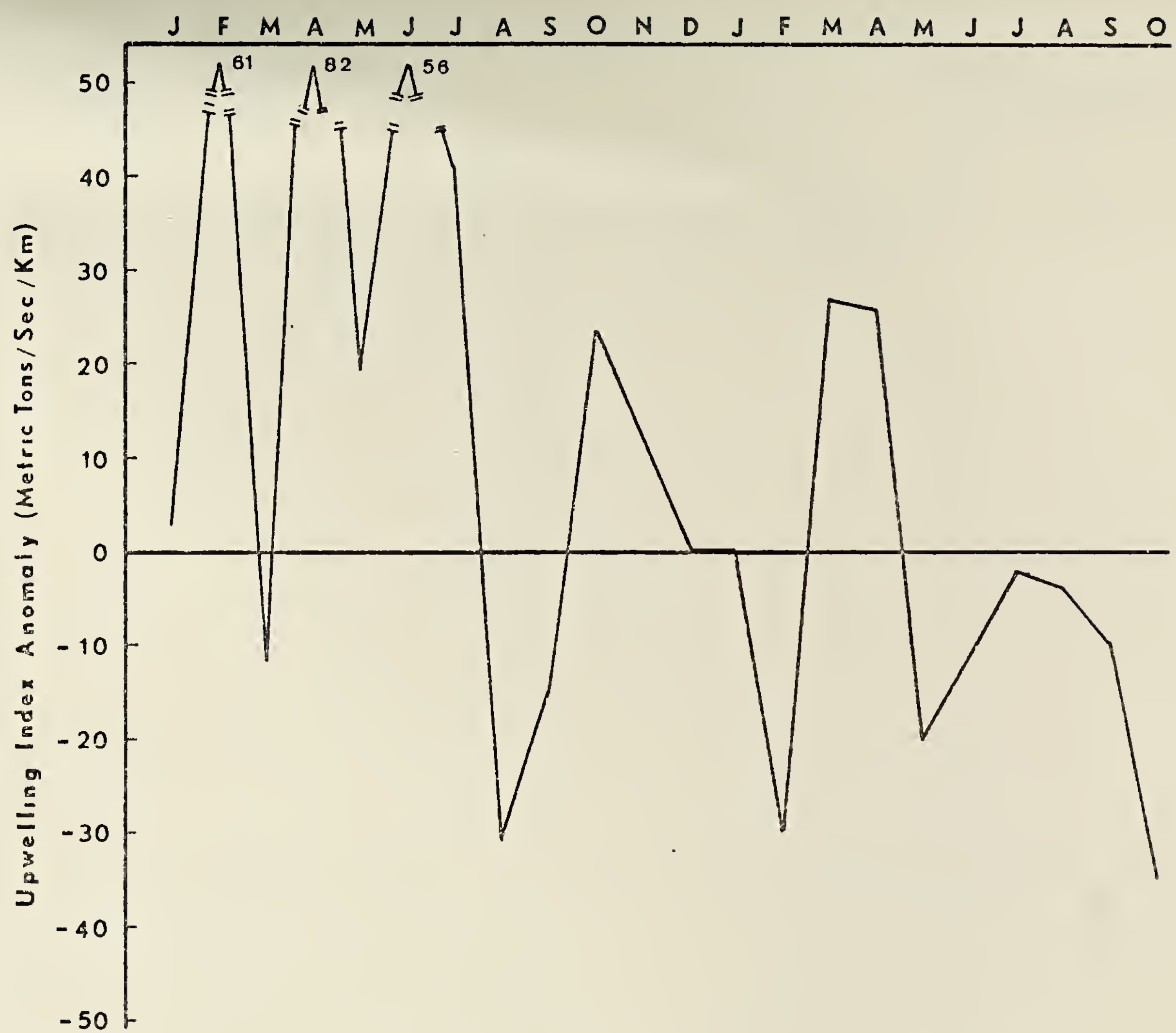


Figure 4. 1971-1972 Upwelling Index Anomaly Values

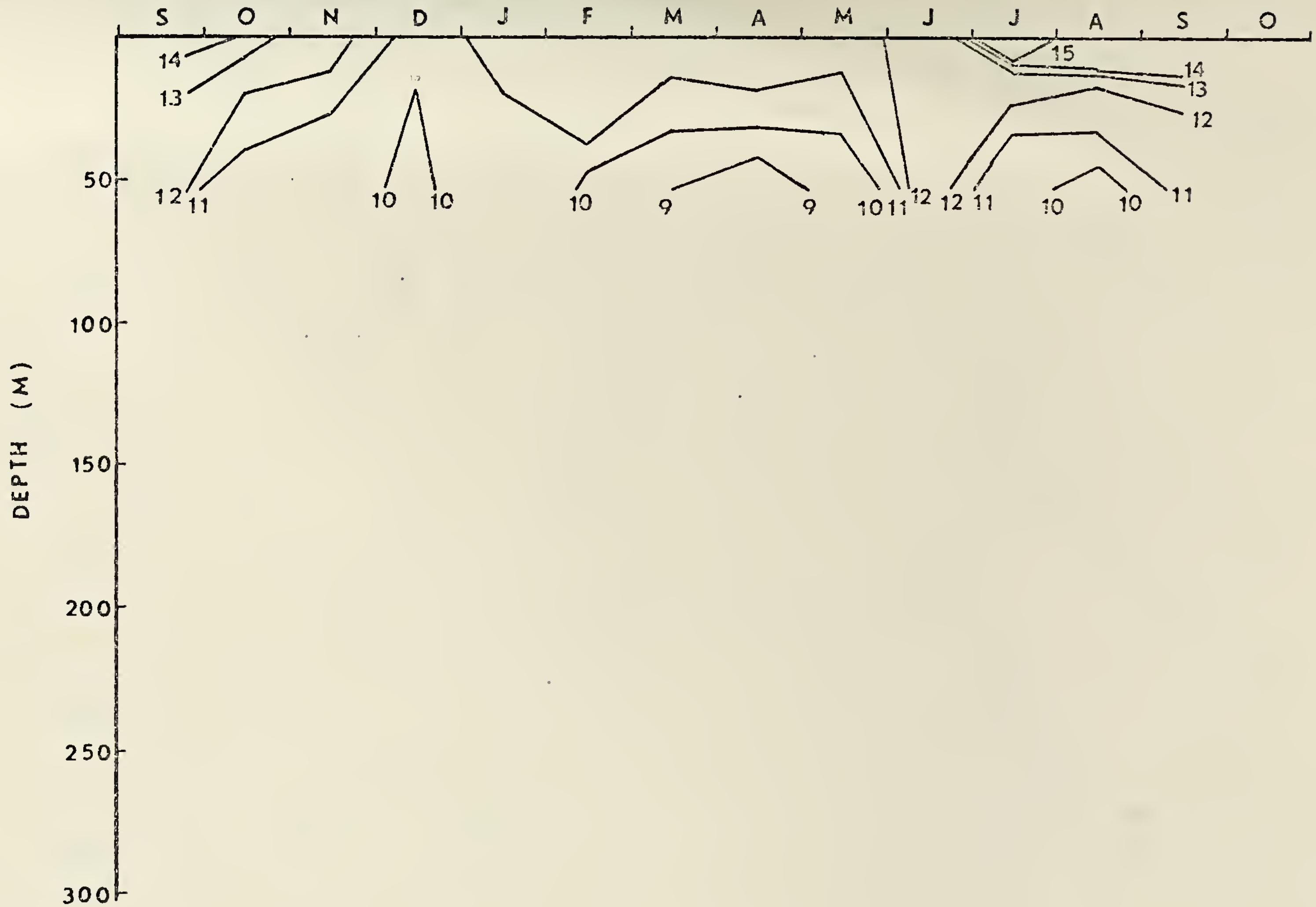


Figure 5. [illegible] Fluctuation at Station 1

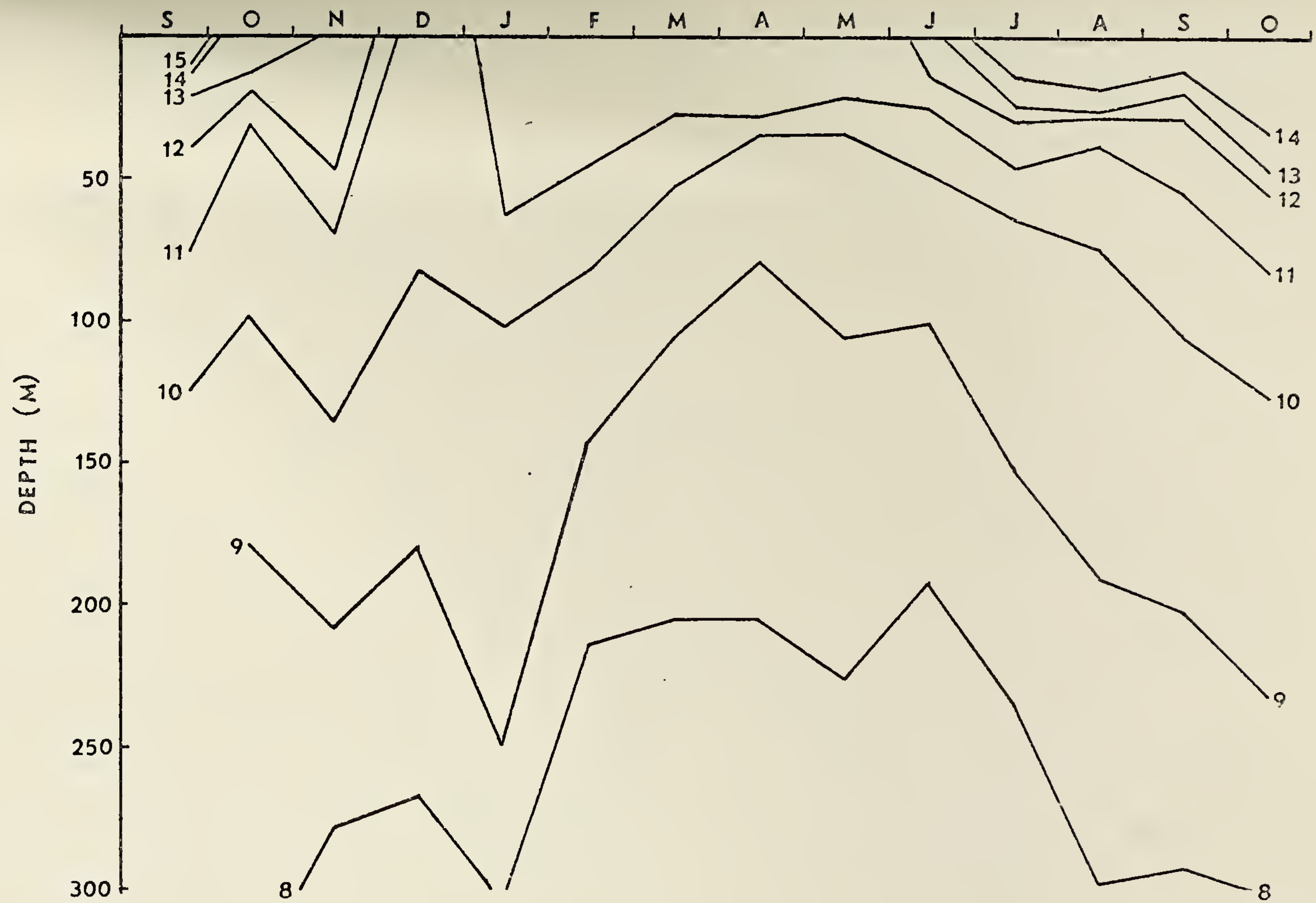


Figure 6. Isotherm Fluctuations at Station 2

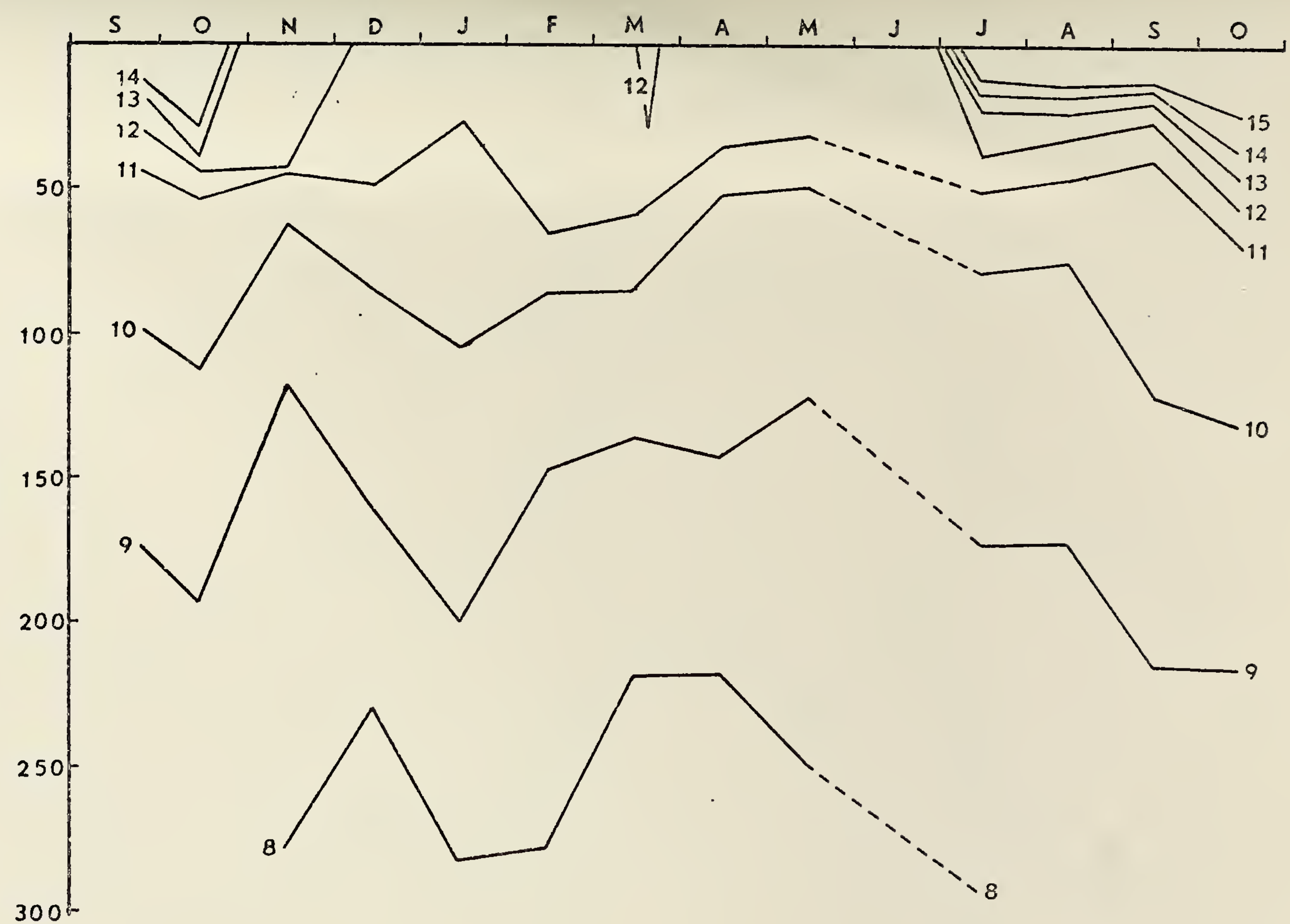


Figure 7. Isotherm Fluctuations at Station 3

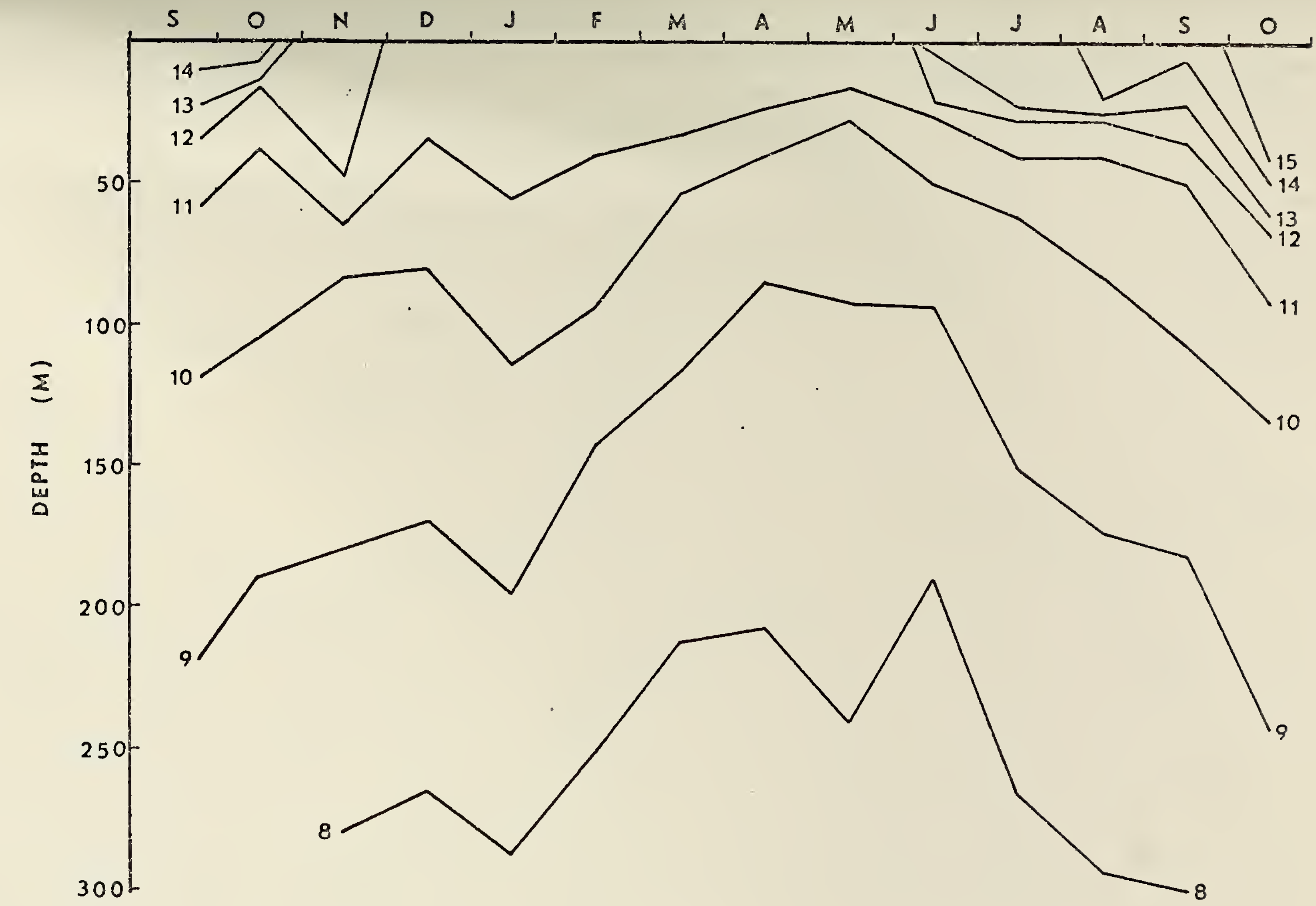


Figure 8. Isotherm Fluctuations at Station 4

Figure 9. Isotherm Fluctuations at Station 5

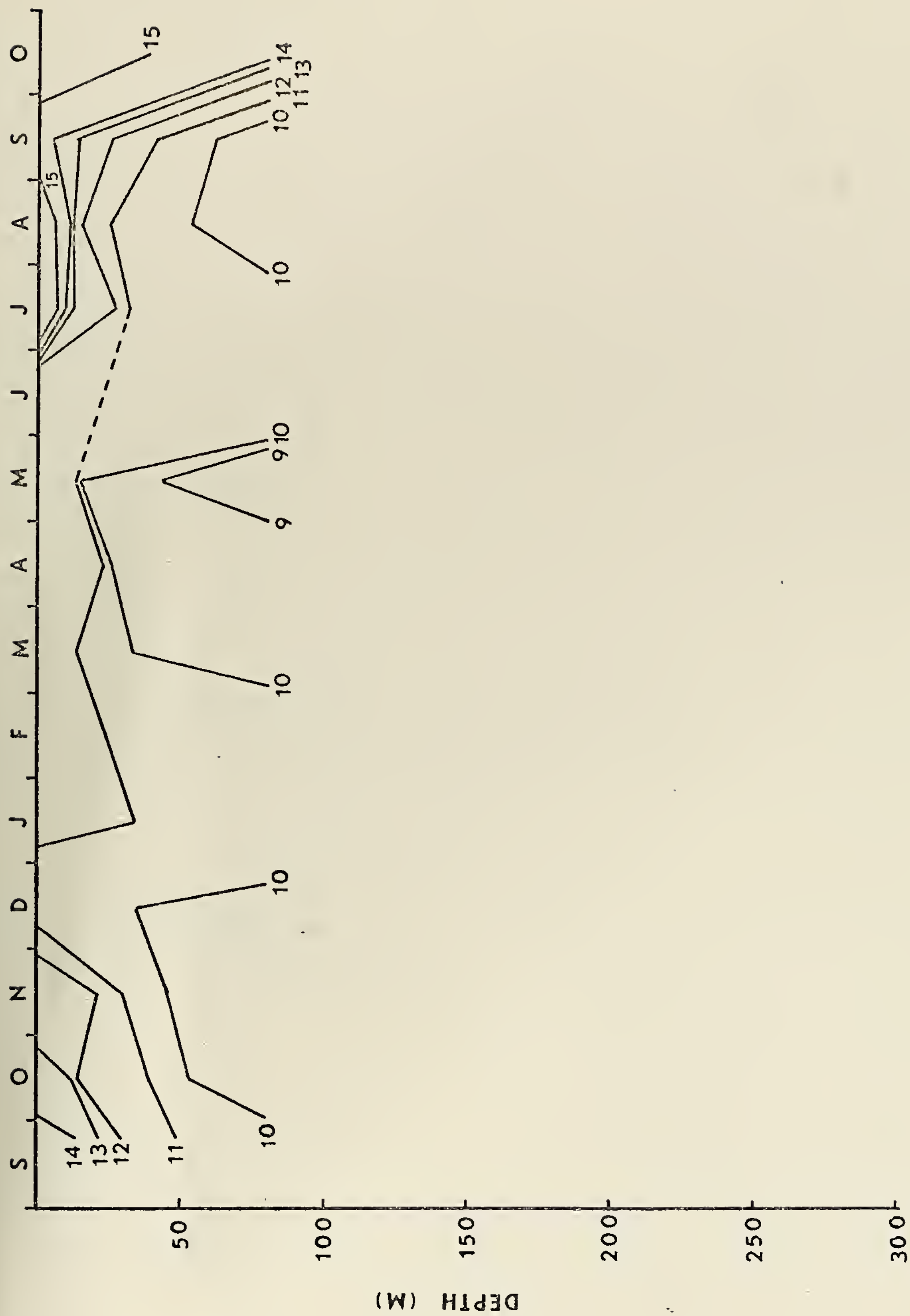
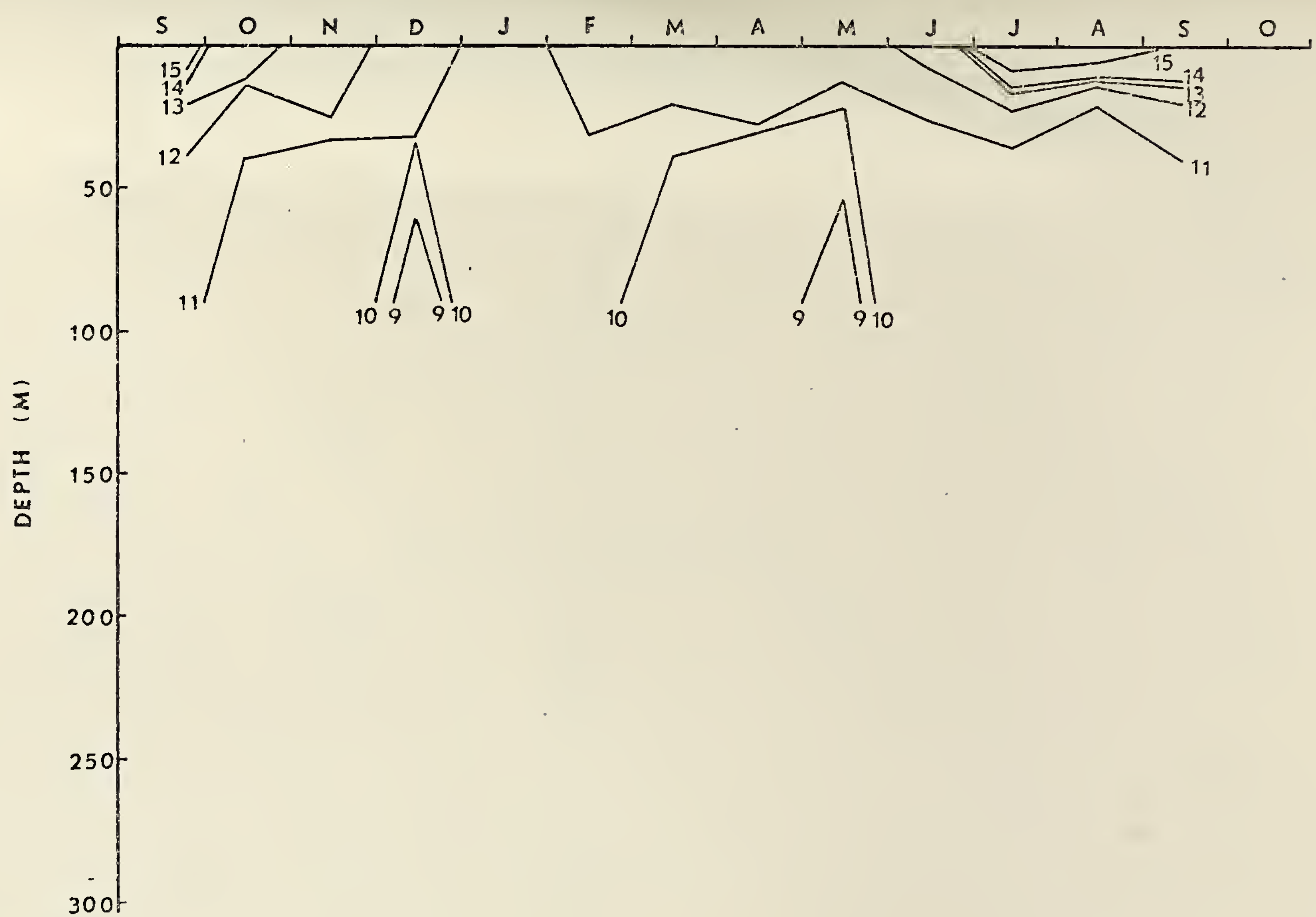


Figure 10. Isotherm Fluctuations at Station 6



Fi 11 -otherm Fluctuations at Station 7

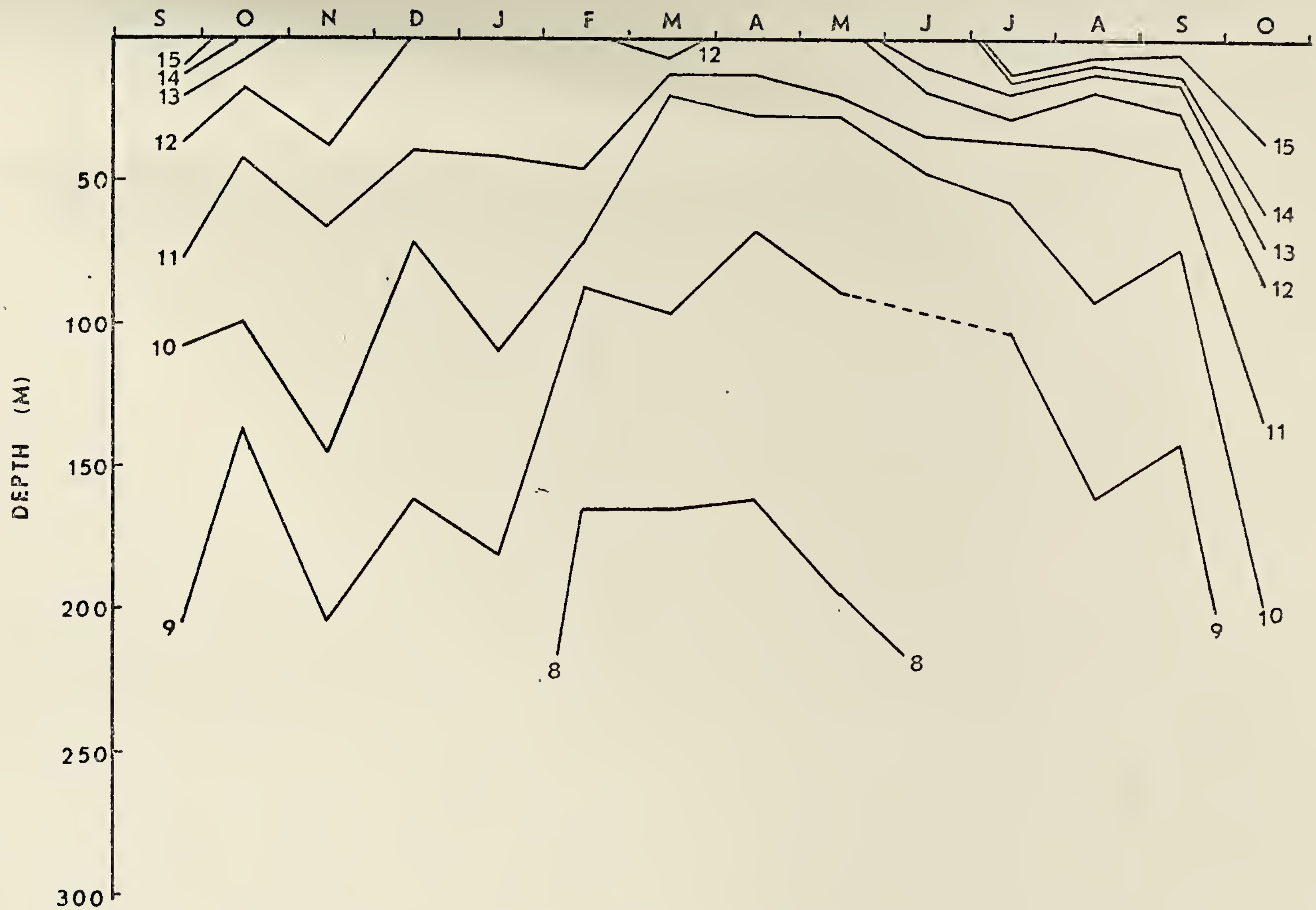


Figure 12. Isotherm Fluctuations at Station 8

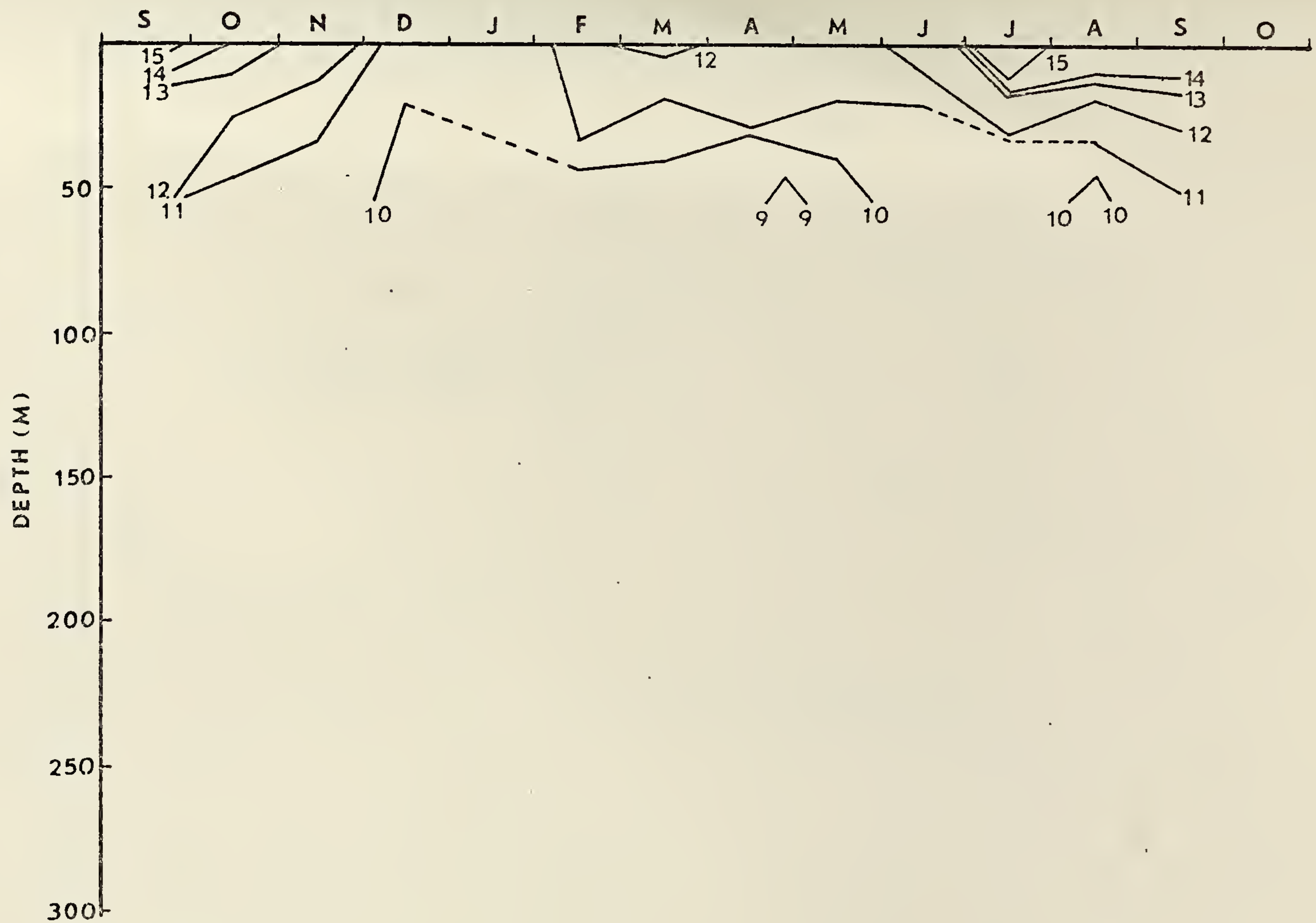


Figure 13. Isotherm Fluctuations at Station 9

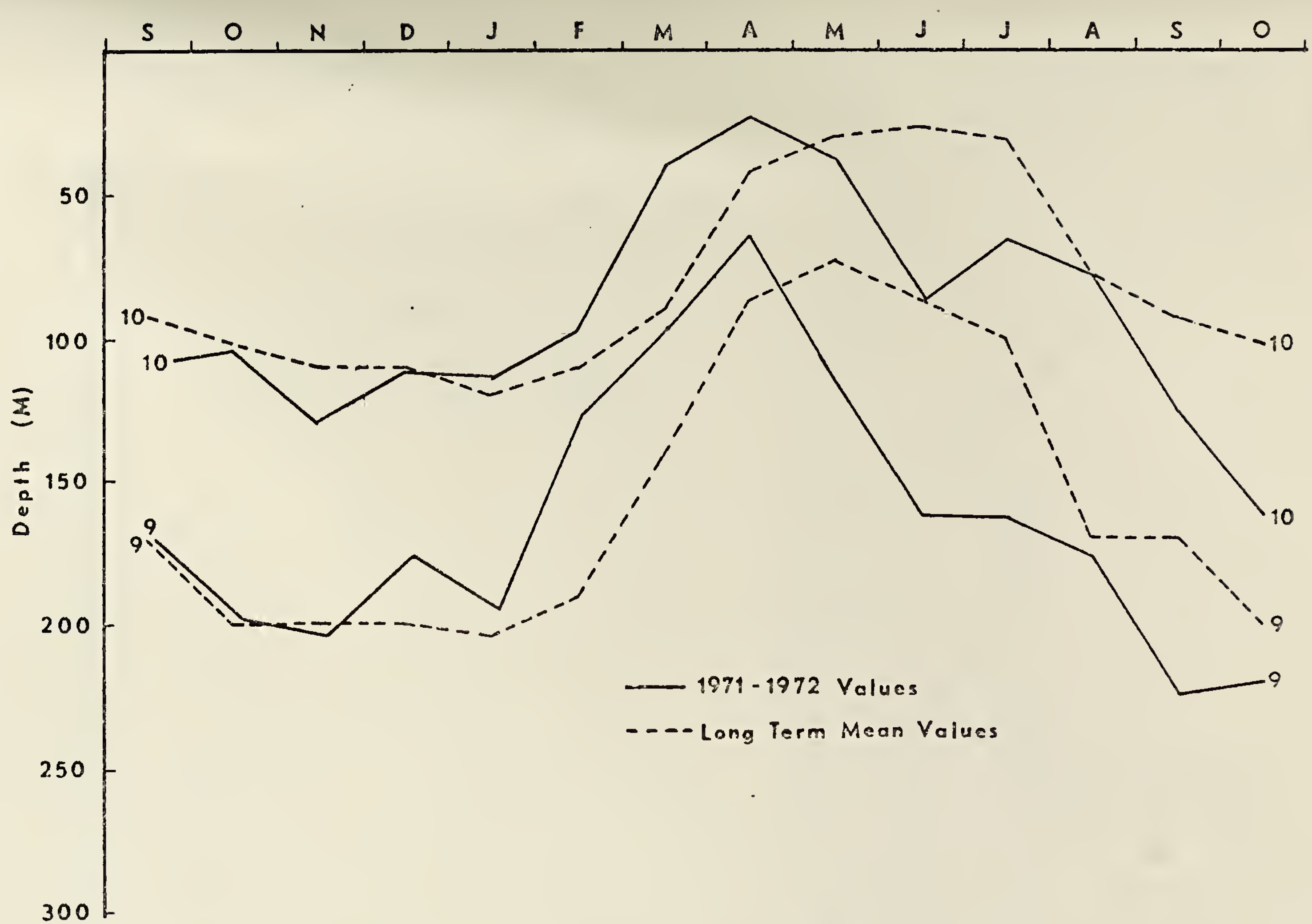


Figure 14. Comparison of Monthly Depths of the 9°C and 10°C Isotherms at Station 5 to Long Term Mean Depths

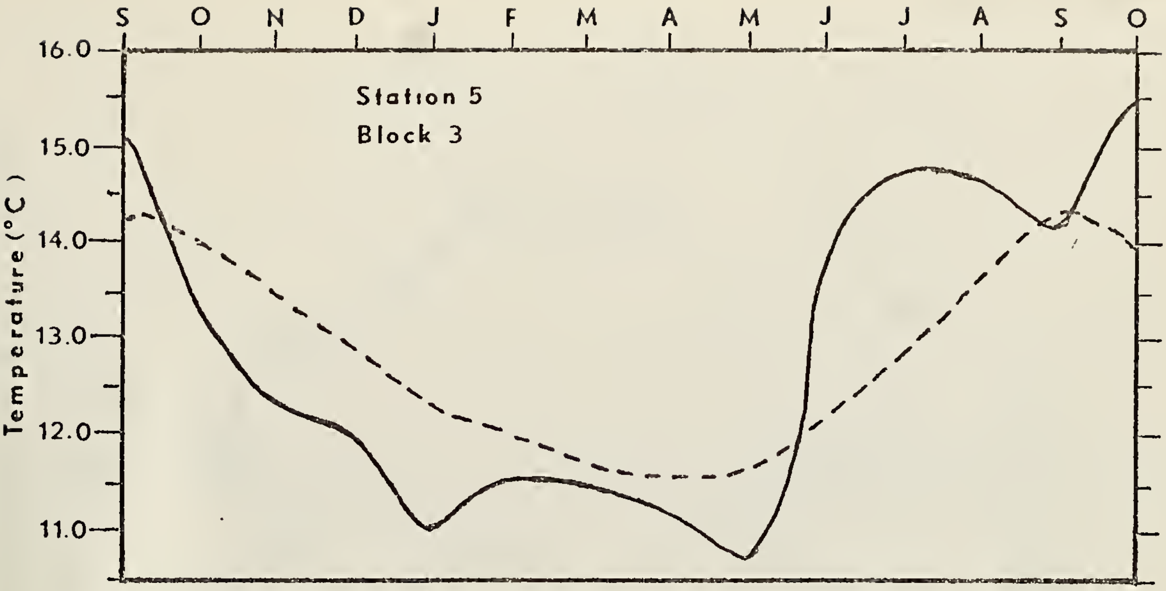


Figure 15. Comparison of 1971-1972 Sea Surface Temperature at Station 5 to Long Term Mean Values

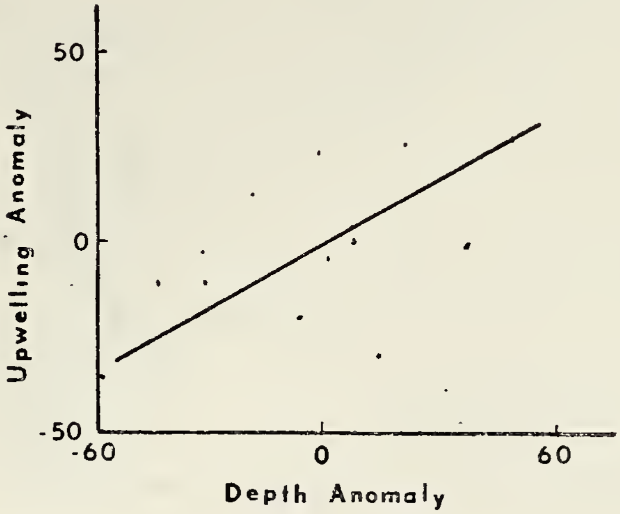


Figure 15A. Comparison of Upwelling Index Anomaly to the Temperature Anomaly at Station 5

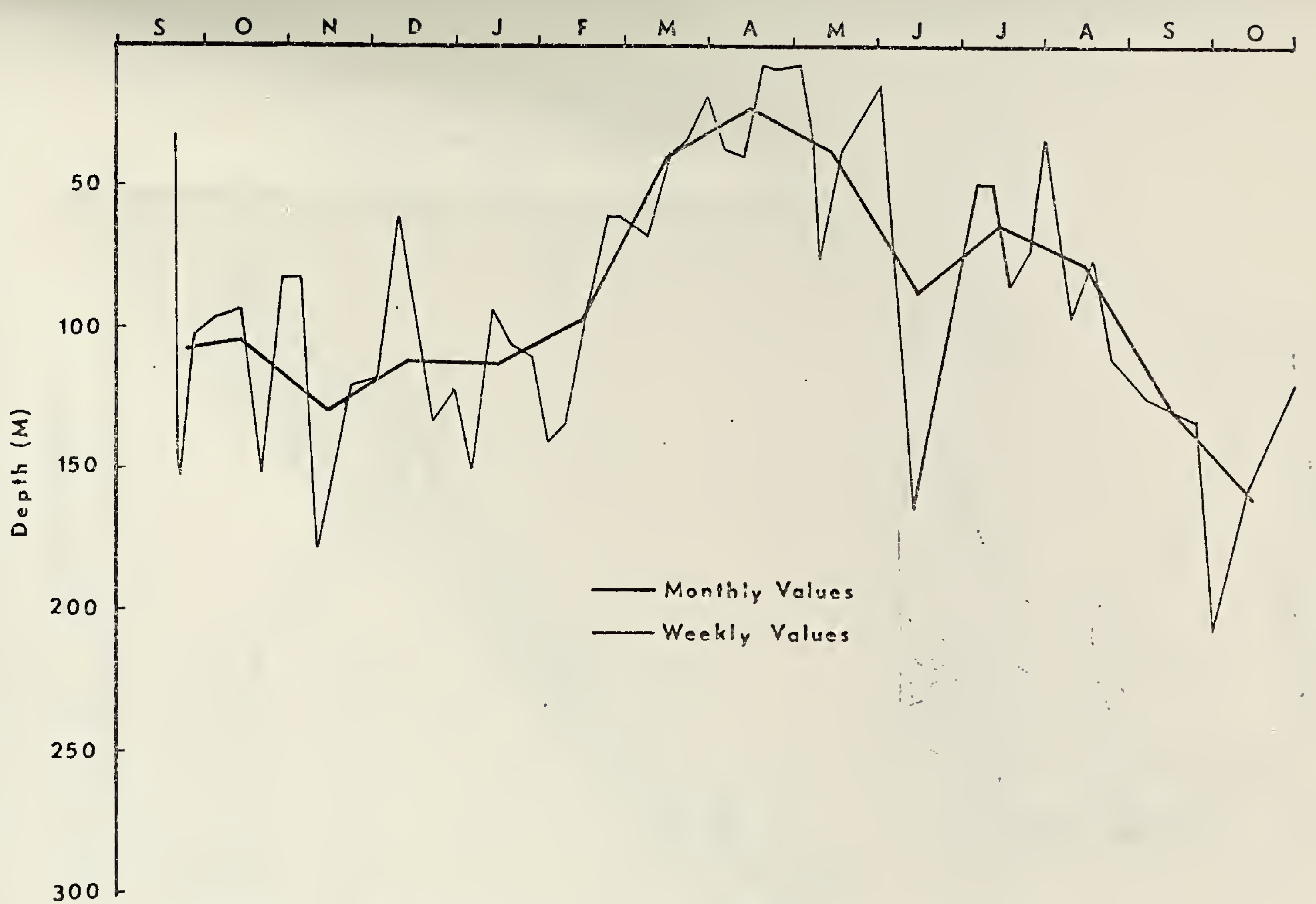


Figure 16. Weekly Fluctuations in the Depth of 10°C Isotherm at Station 5

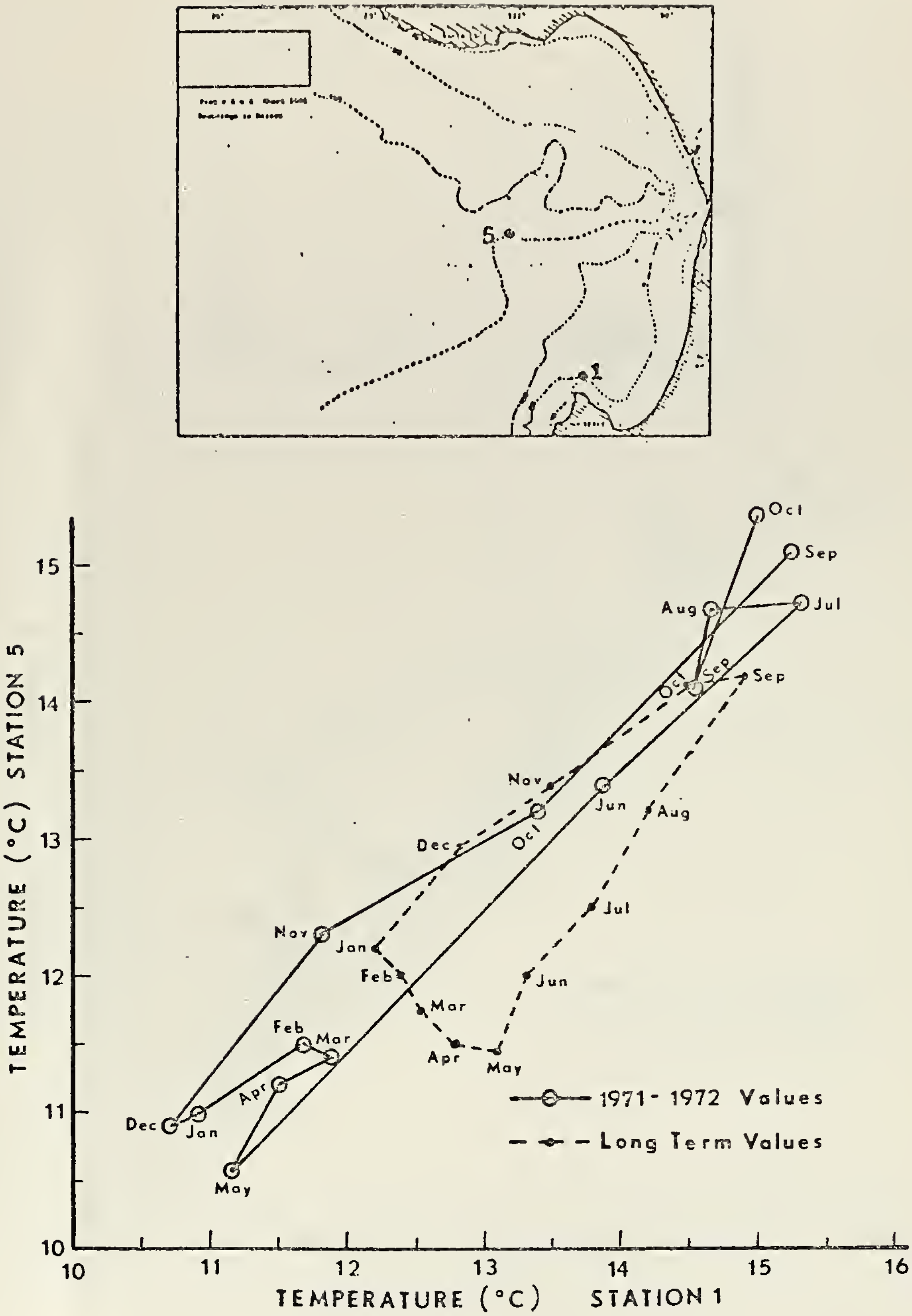


Figure 17. Comparison of Monthly Sea Surface Temperature at Station 1 and Station 5 to Long Term Mean Monthly Values

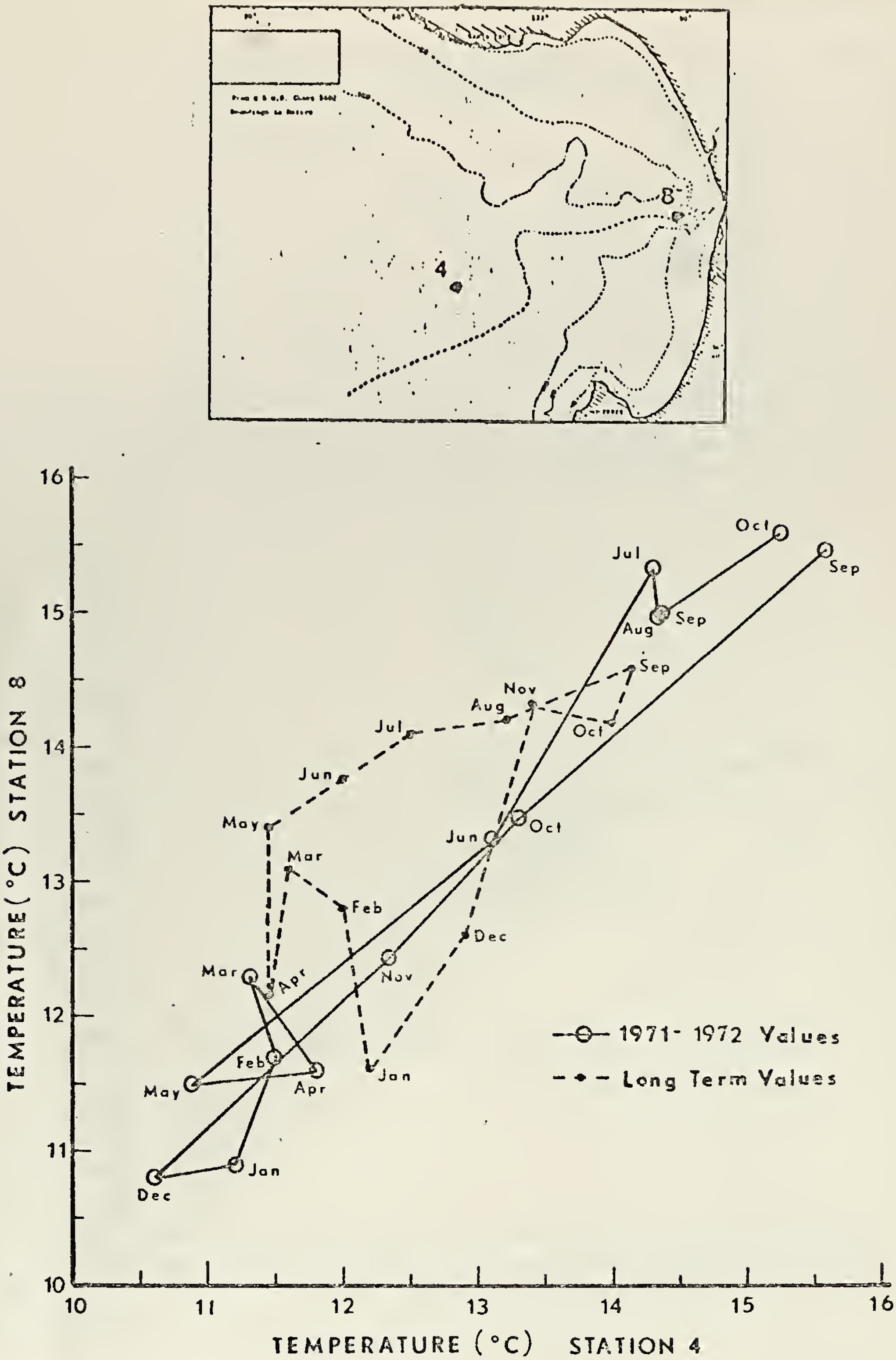
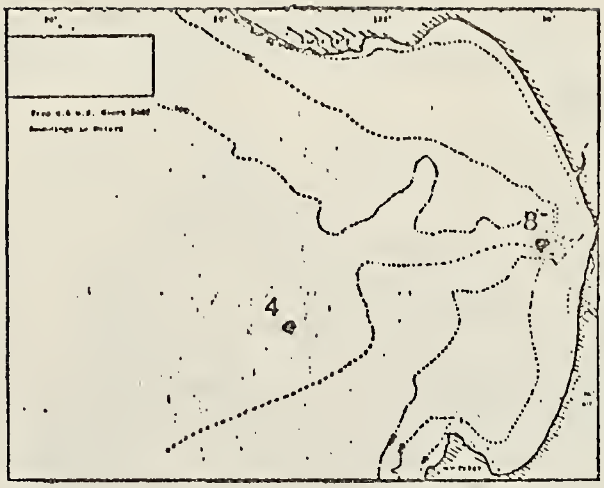


Figure 18. Comparison of Monthly Sea Surface Temperature at Stations 4 and 8 to Long Term Mean Monthly Values



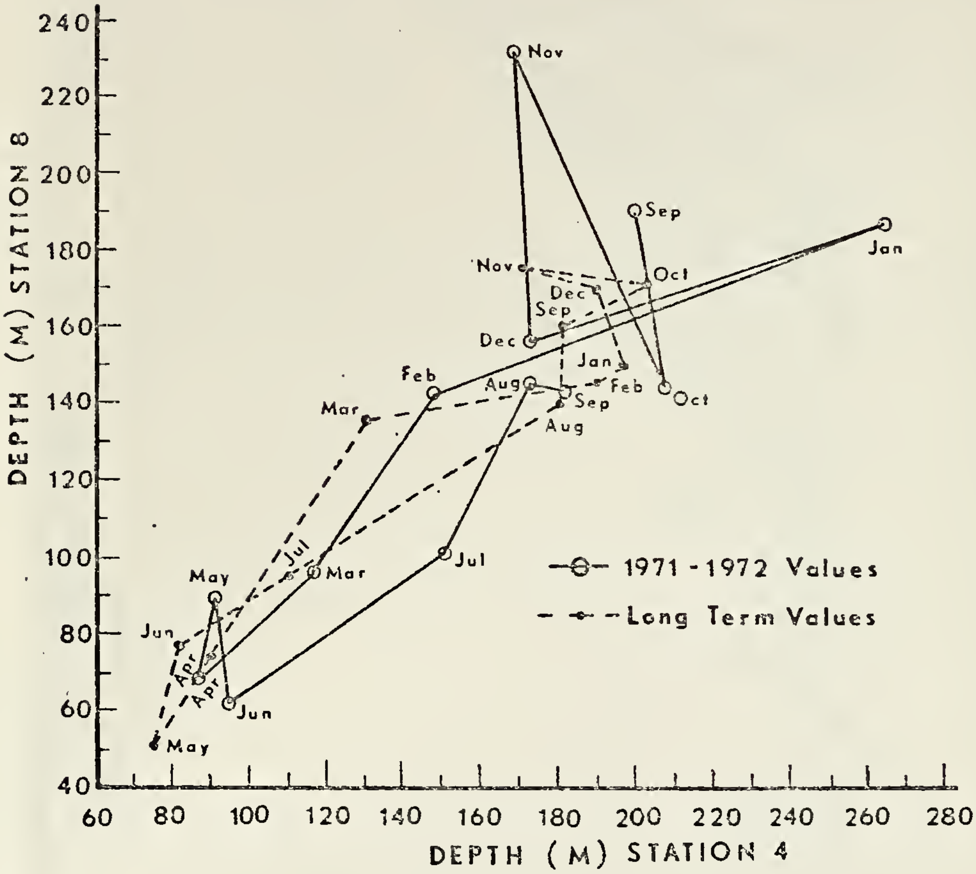


Figure 19. Comparison of Monthly Depth of 9°C Isotherm at Station 4 and Station 8 to Long Term Mean Monthly Depths

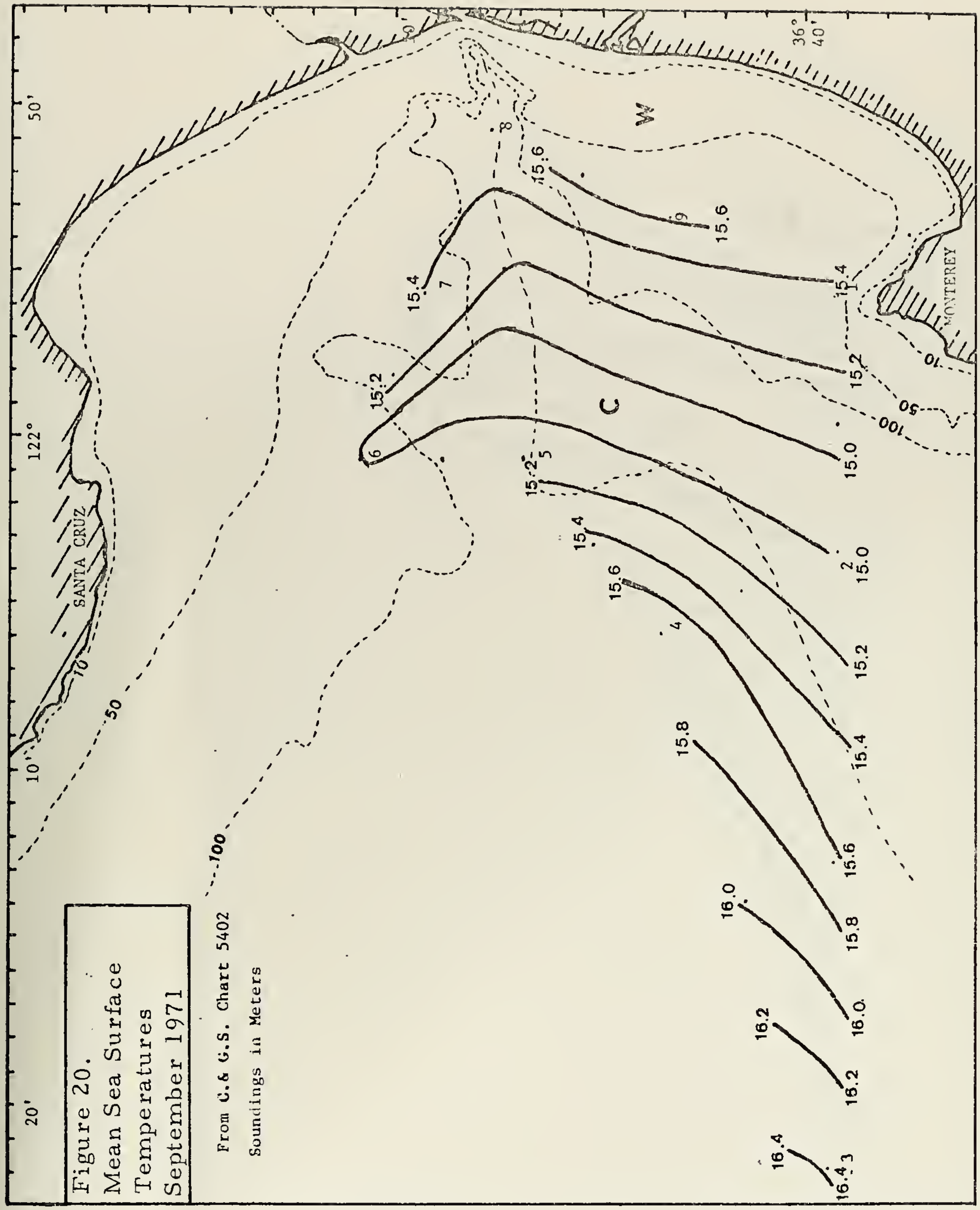


Figure 20. Mean Sea Surface Temperatures September 1971

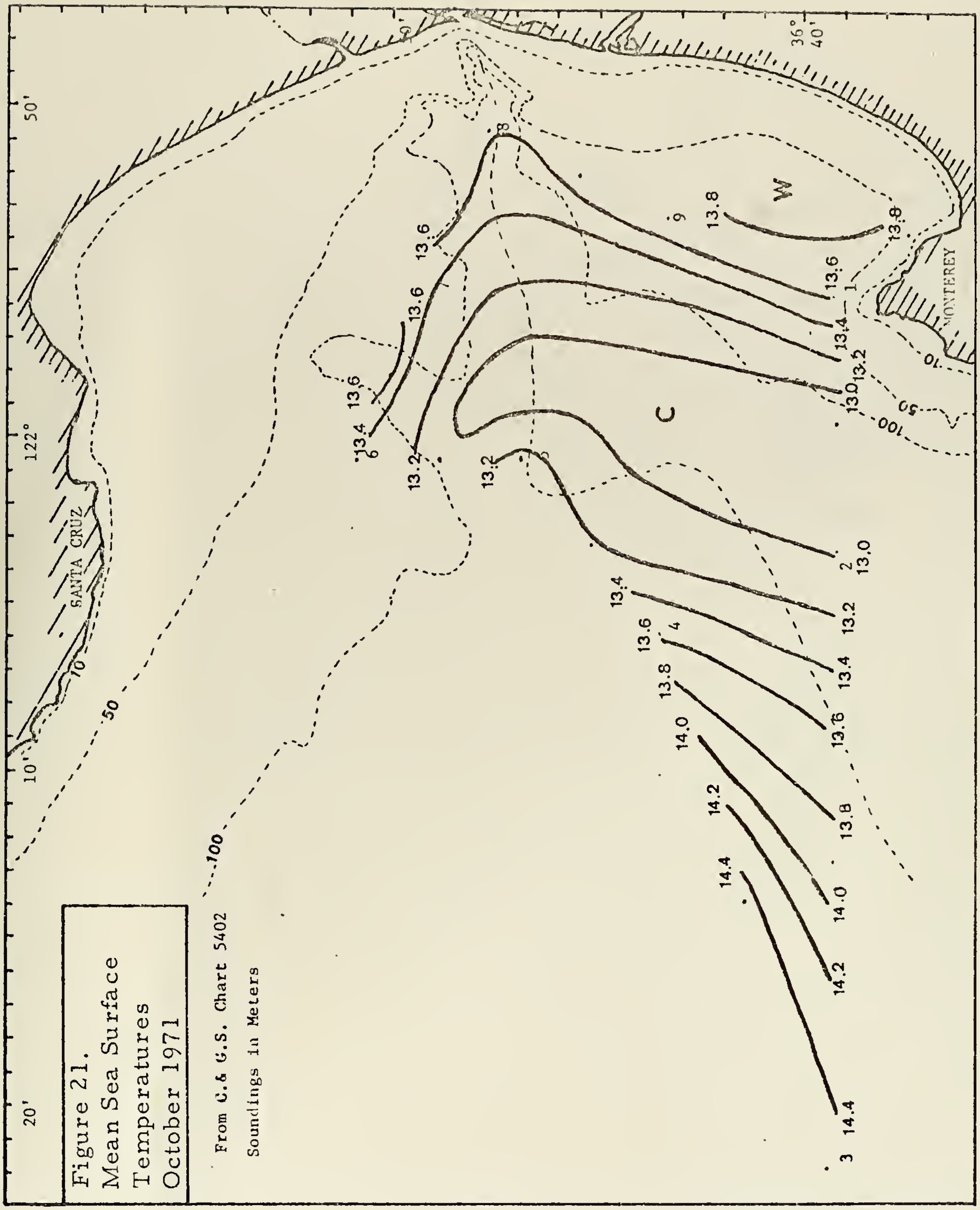


Figure 21.
Mean Sea Surface
Temperatures
October 1971

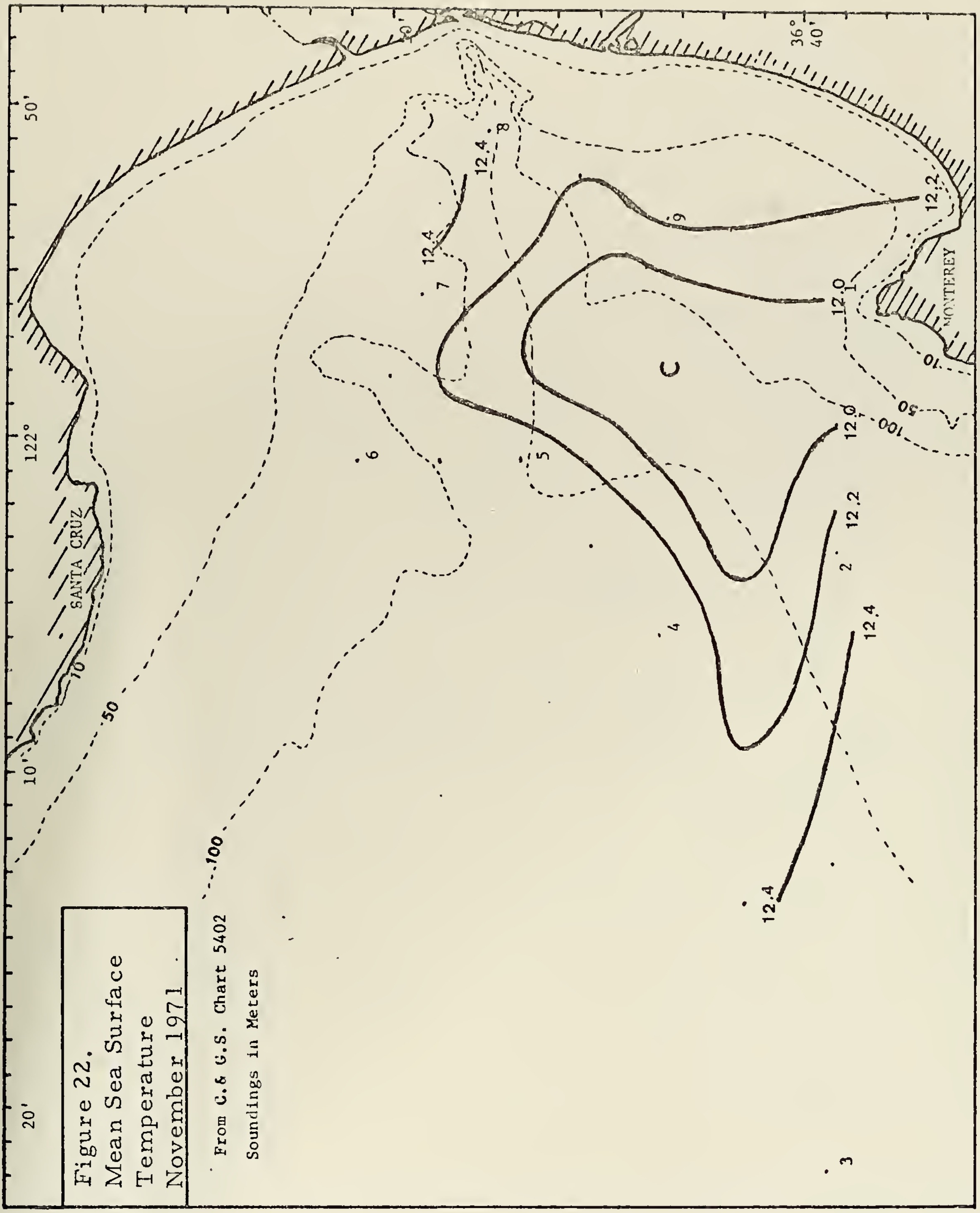


Figure 22. Mean Sea Surface Temperature November 1971

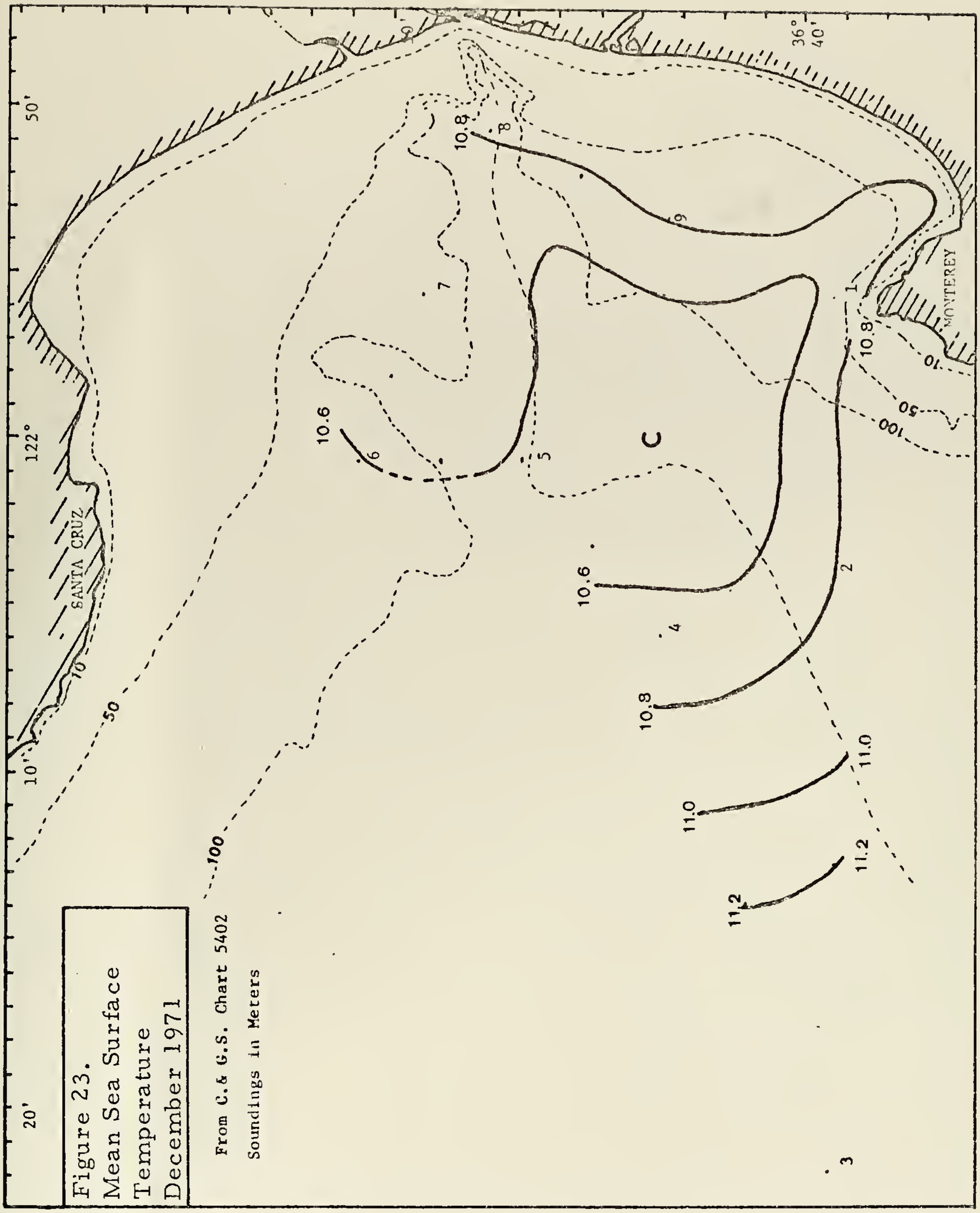


Figure 23.
Mean Sea Surface
Temperature
December 1971

From C.& G.S. Chart 5402
Soundings in Meters

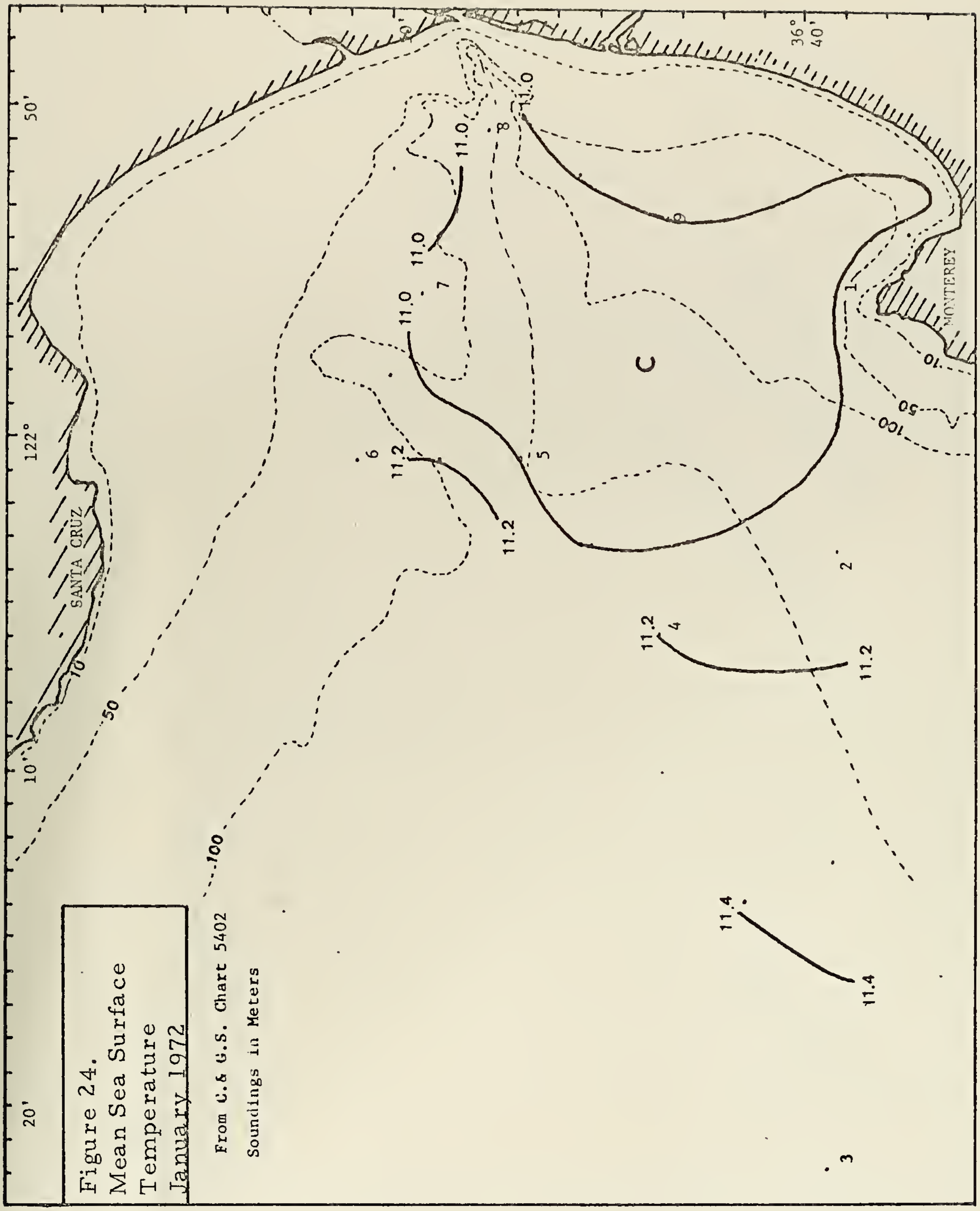


Figure 24.
Mean Sea Surface
Temperature
January 1972

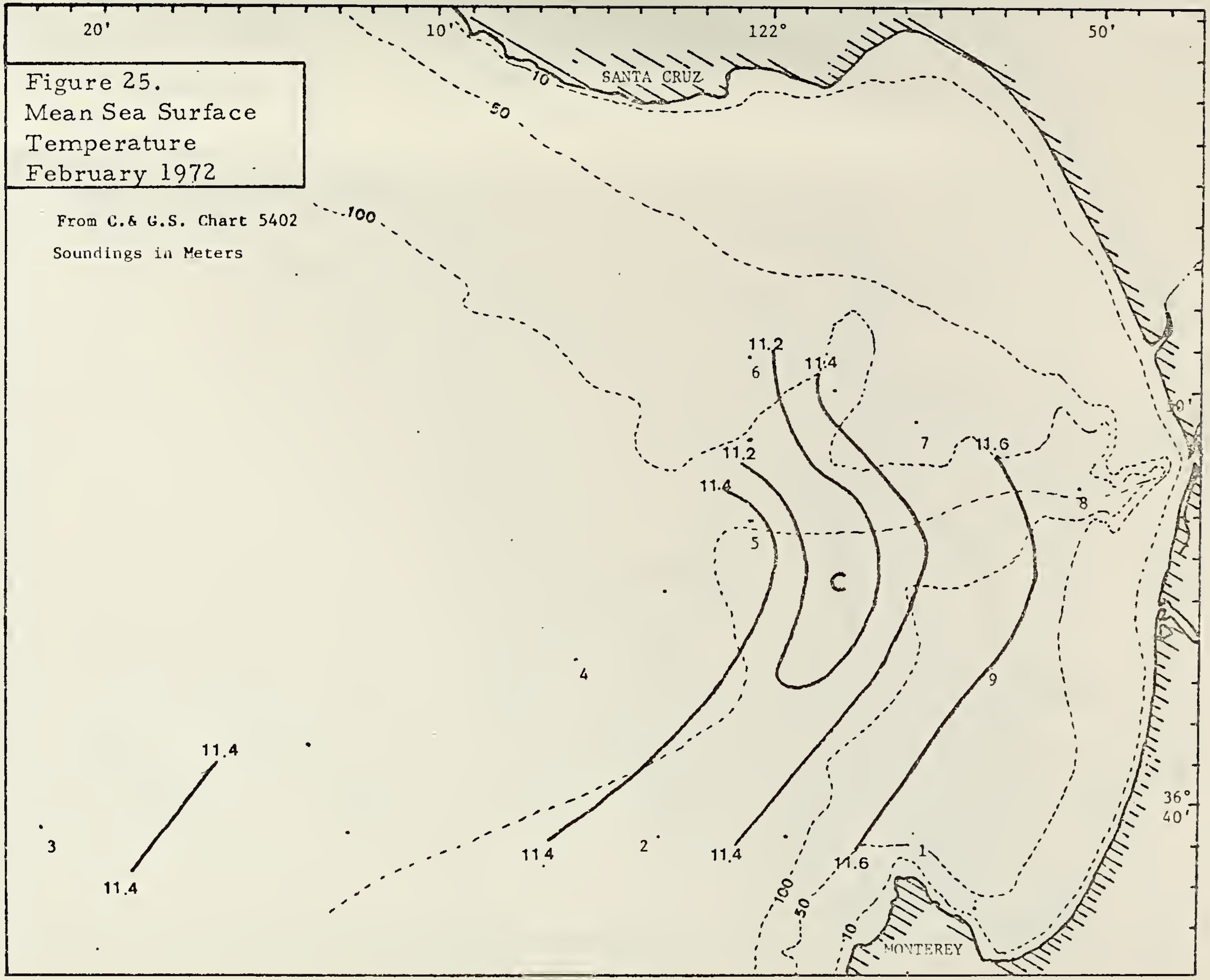


Figure 25.
Mean Sea Surface
Temperature
February 1972

From C.& G.S. Chart 5402
Soundings in Meters

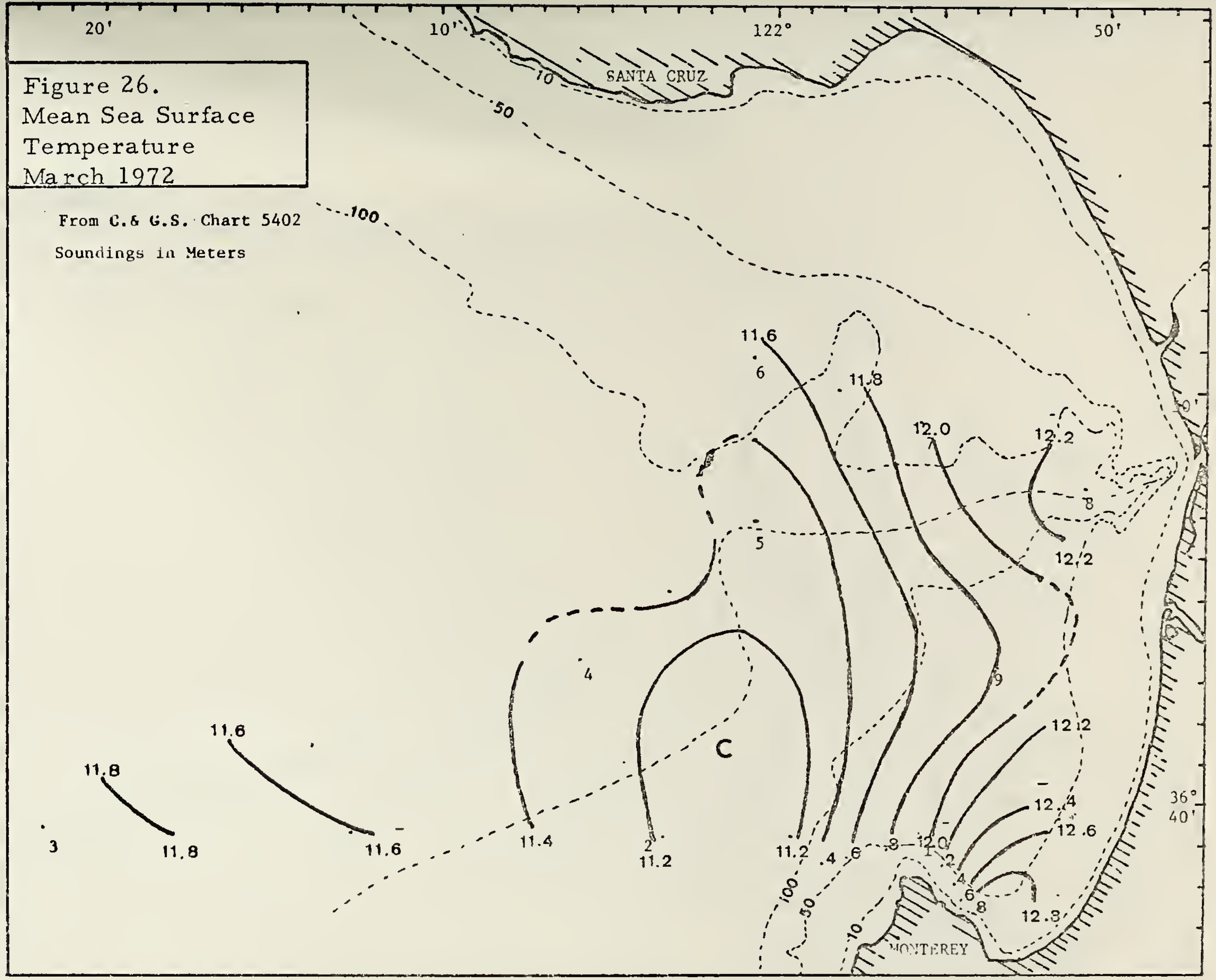


Figure 26.
Mean Sea Surface
Temperature
March 1972

From C.& G.S. Chart 5402

Soundings in Meters

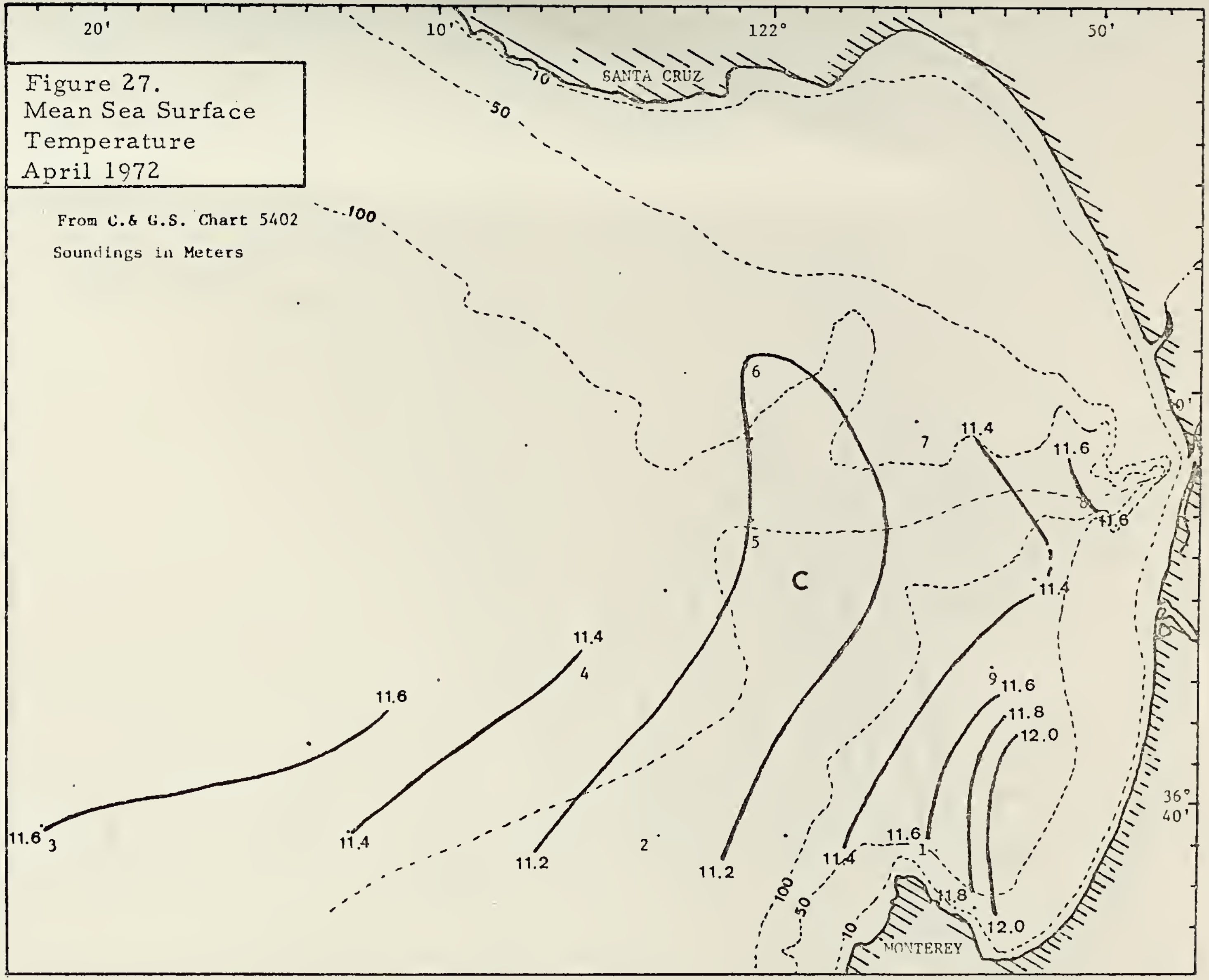


Figure 27.
Mean Sea Surface
Temperature
April 1972

From C.& G.S. Chart 5402
Soundings in Meters

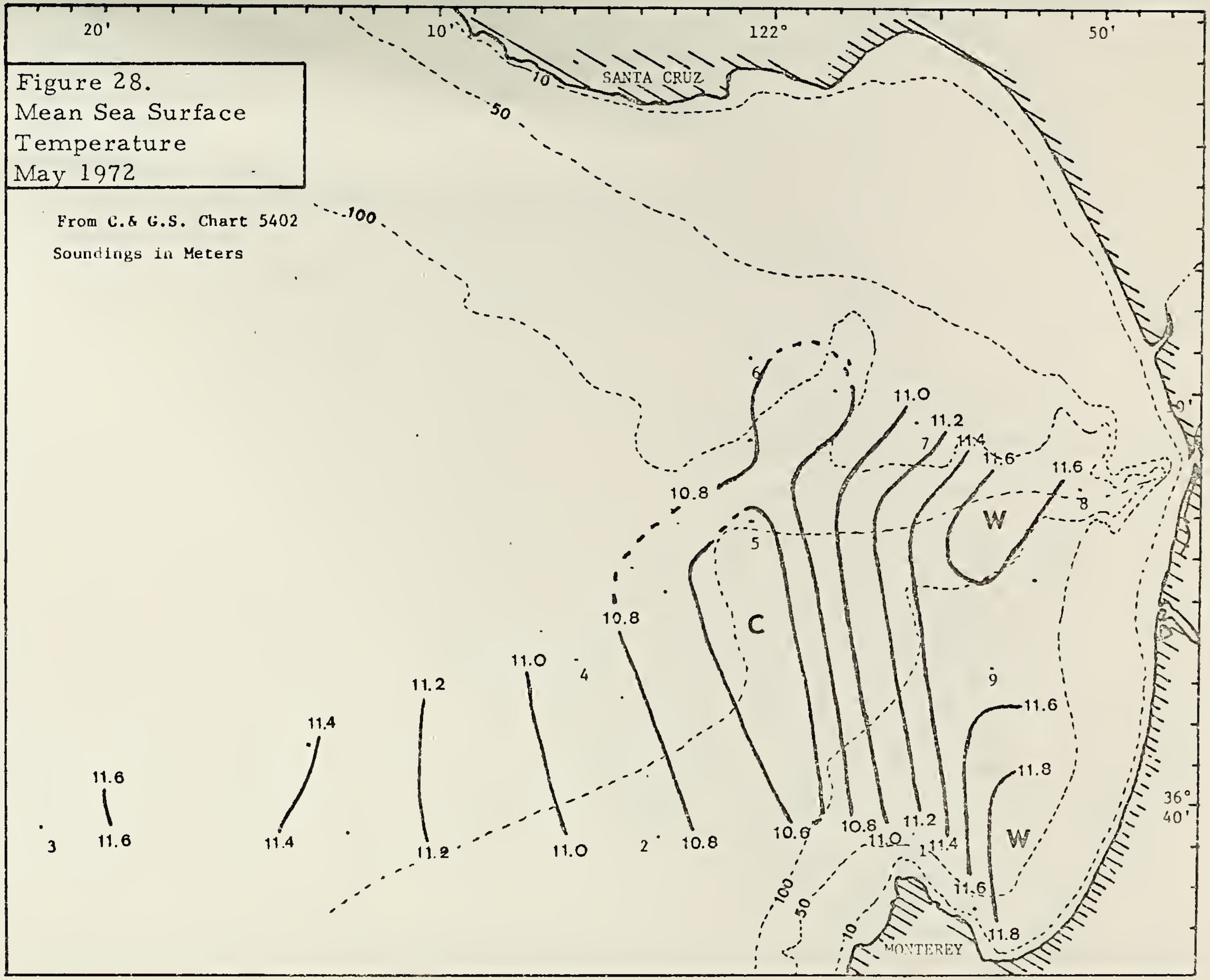


Figure 28.
Mean Sea Surface
Temperature
May 1972

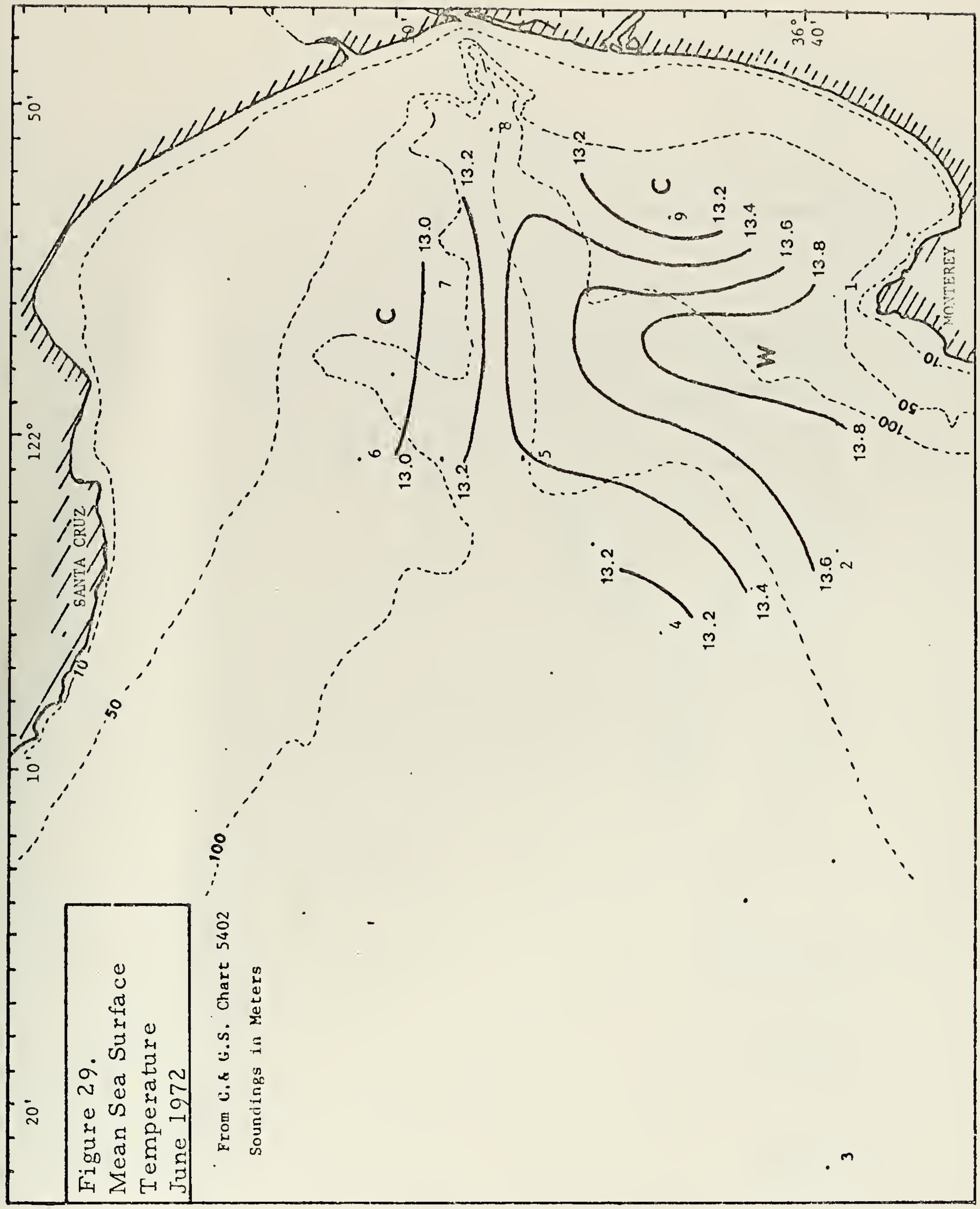


Figure 29.
Mean Sea Surface
Temperature
June 1972

From C.& G.S. Chart 5402
Soundings in Meters

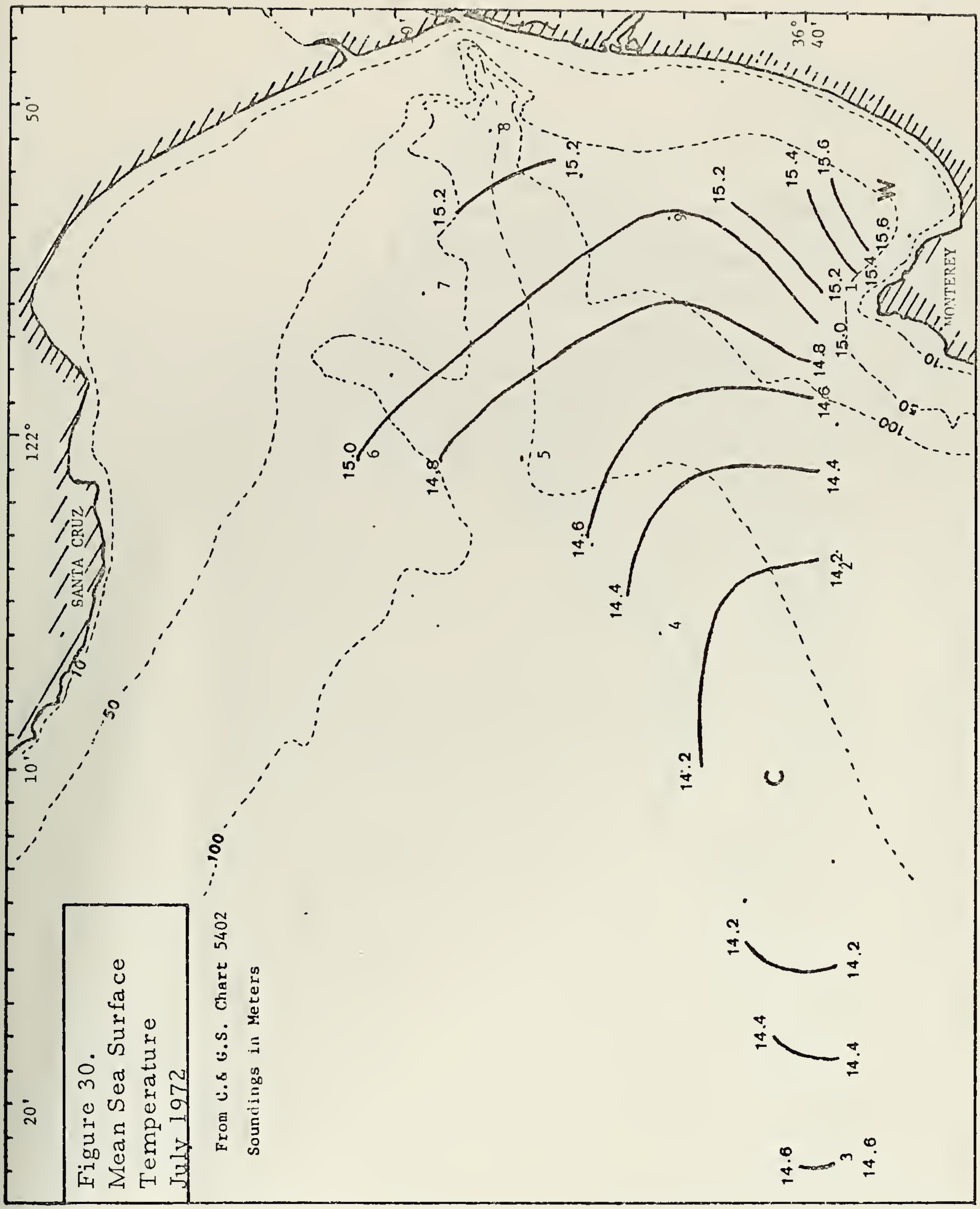


Figure 30. Mean Sea Surface Temperature July 1972

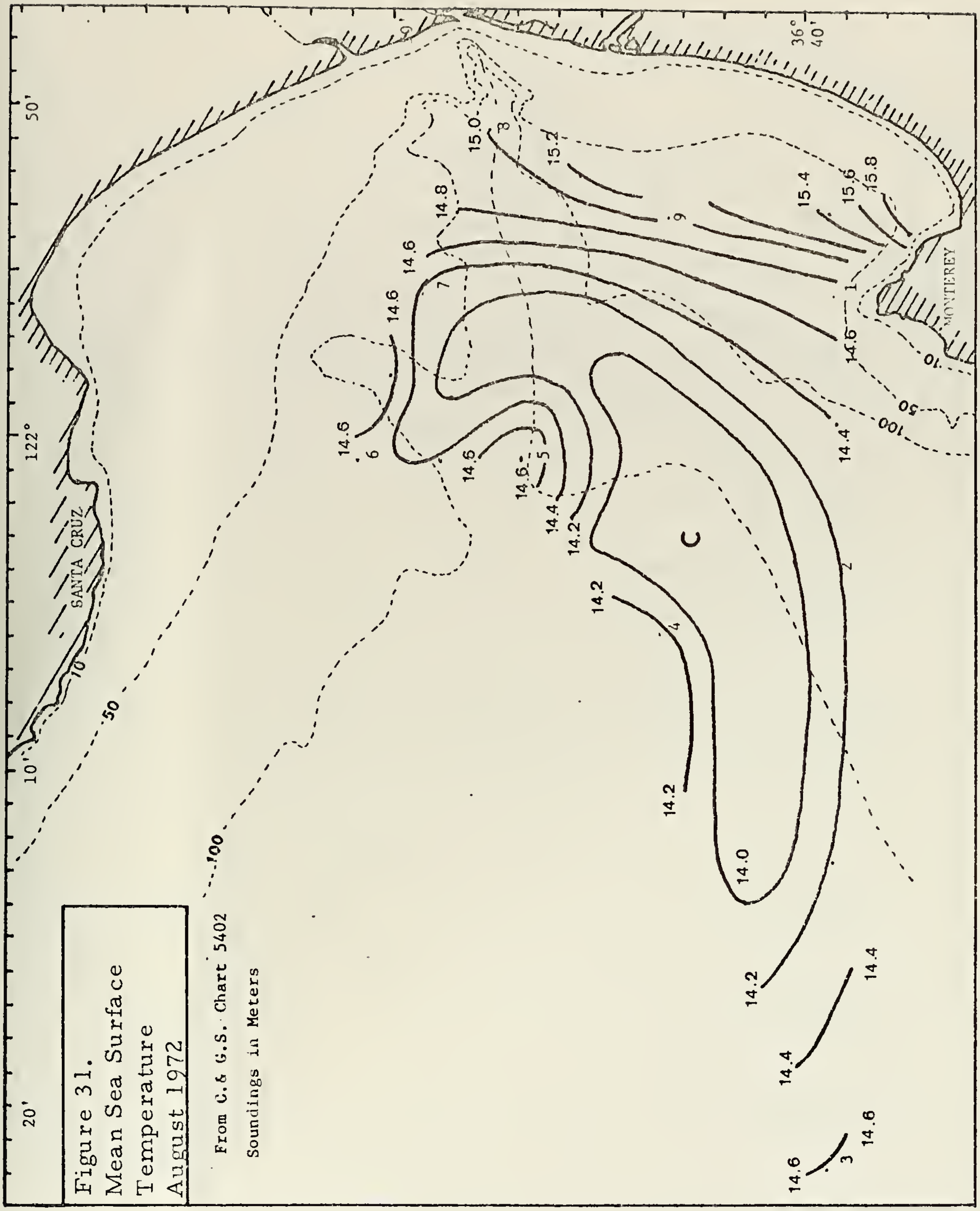


Figure 31.
Mean Sea Surface
Temperature
August 1972

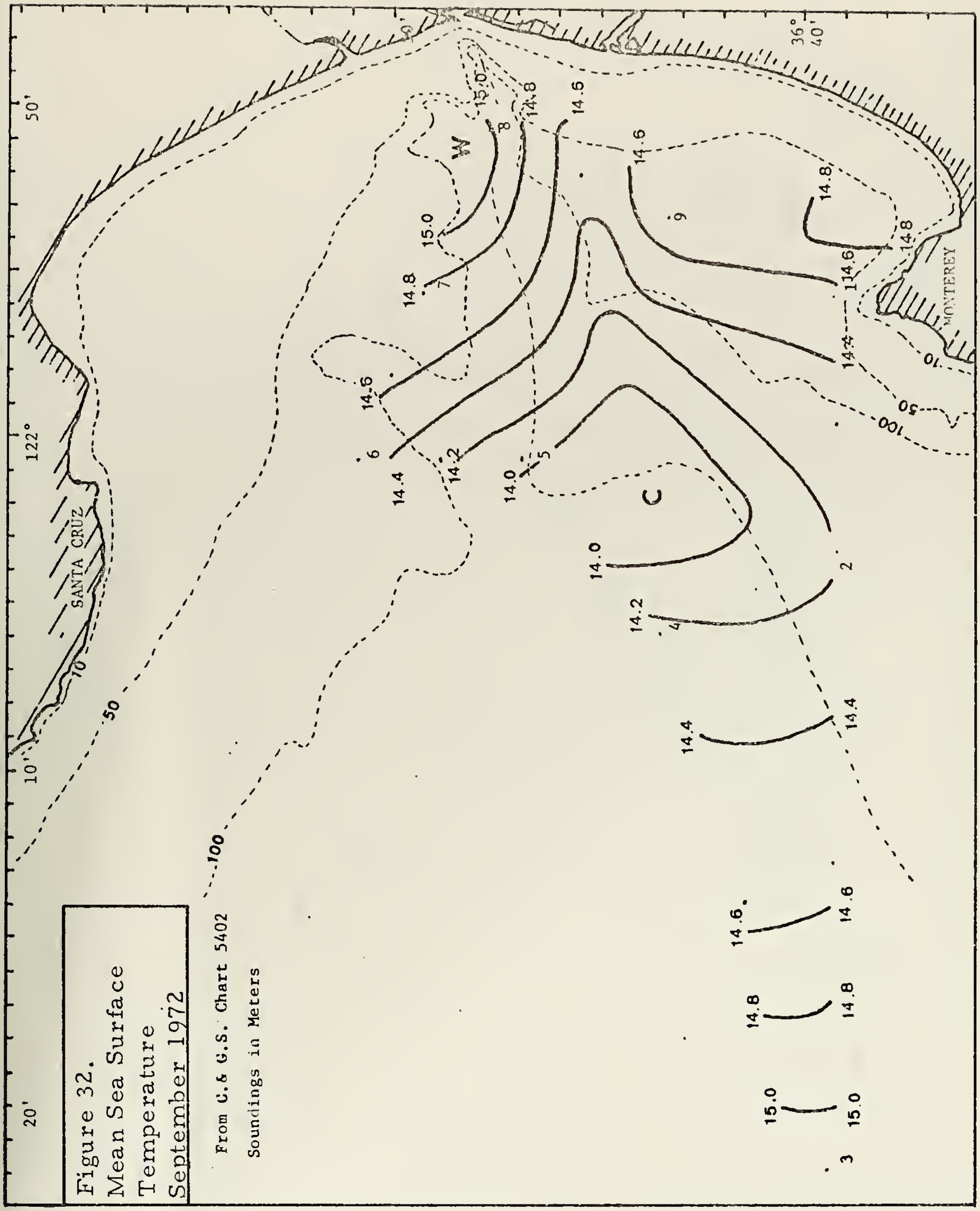


Figure 32.
Mean Sea Surface
Temperature
September 1972

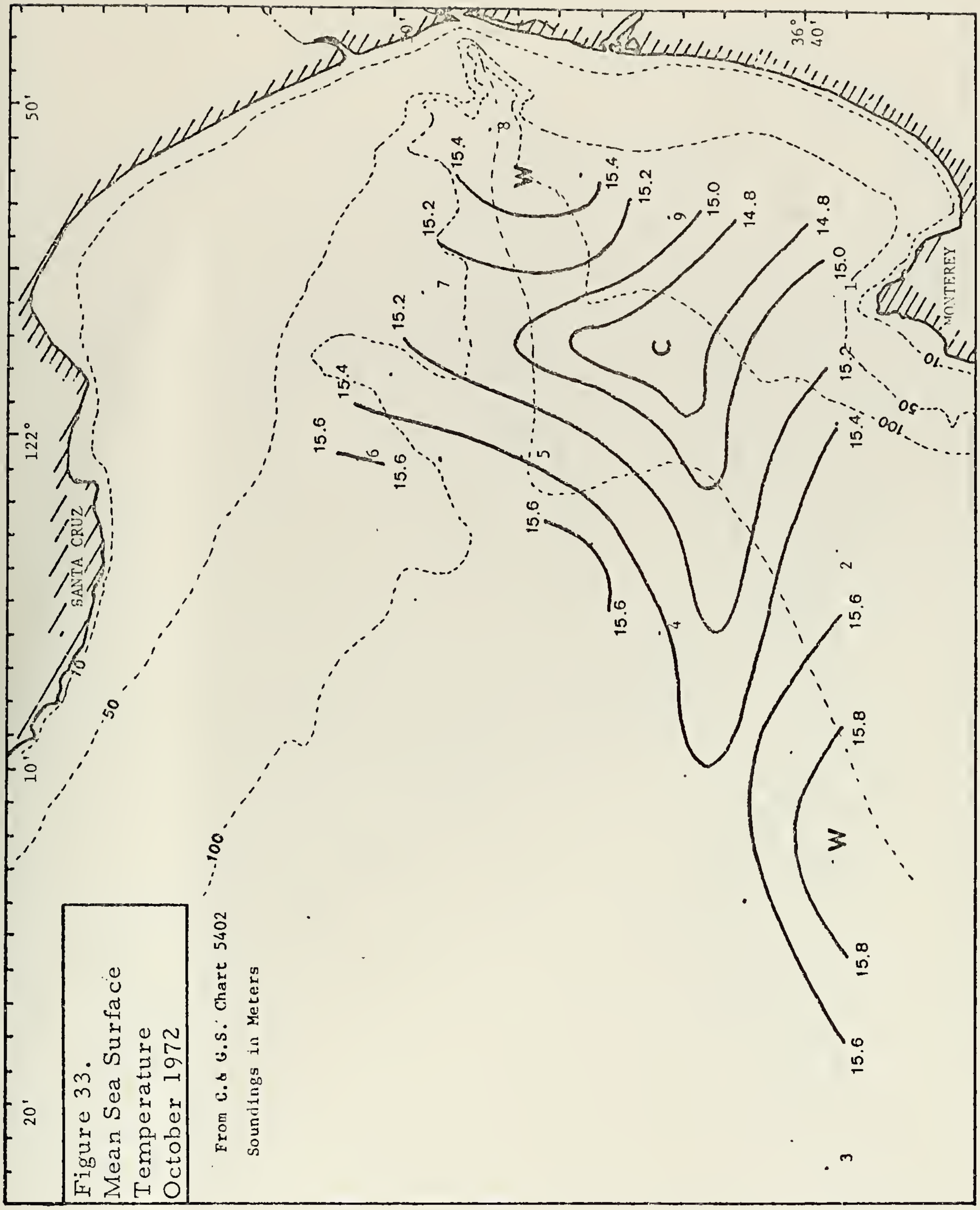


Figure 33.
Mean Sea Surface
Temperature
October 1972

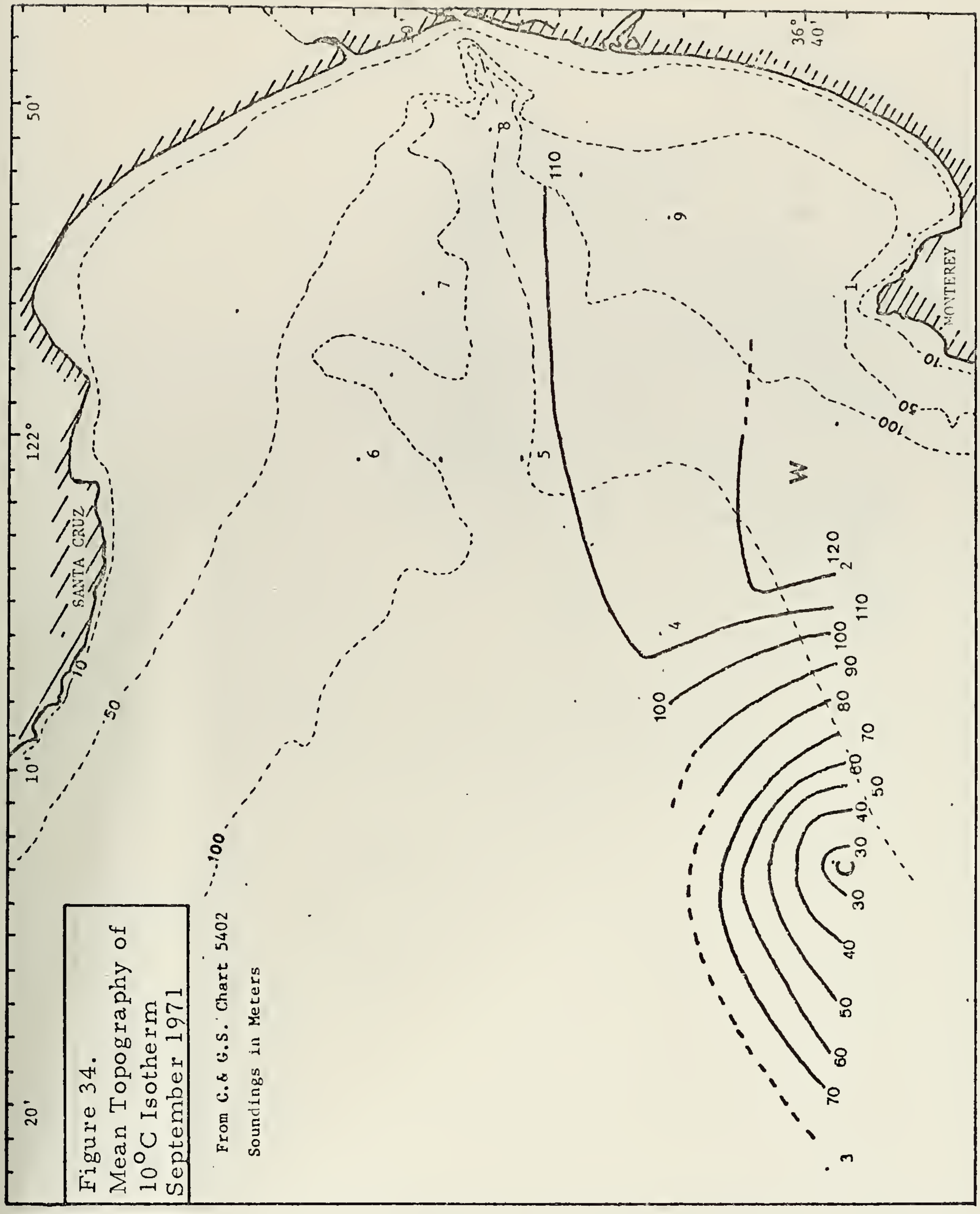


Figure 34.
Mean Topography of
$10^{\circ}C$ Isotherm
September 1971

From C.& G.S. Chart 5402
Soundings in Meters

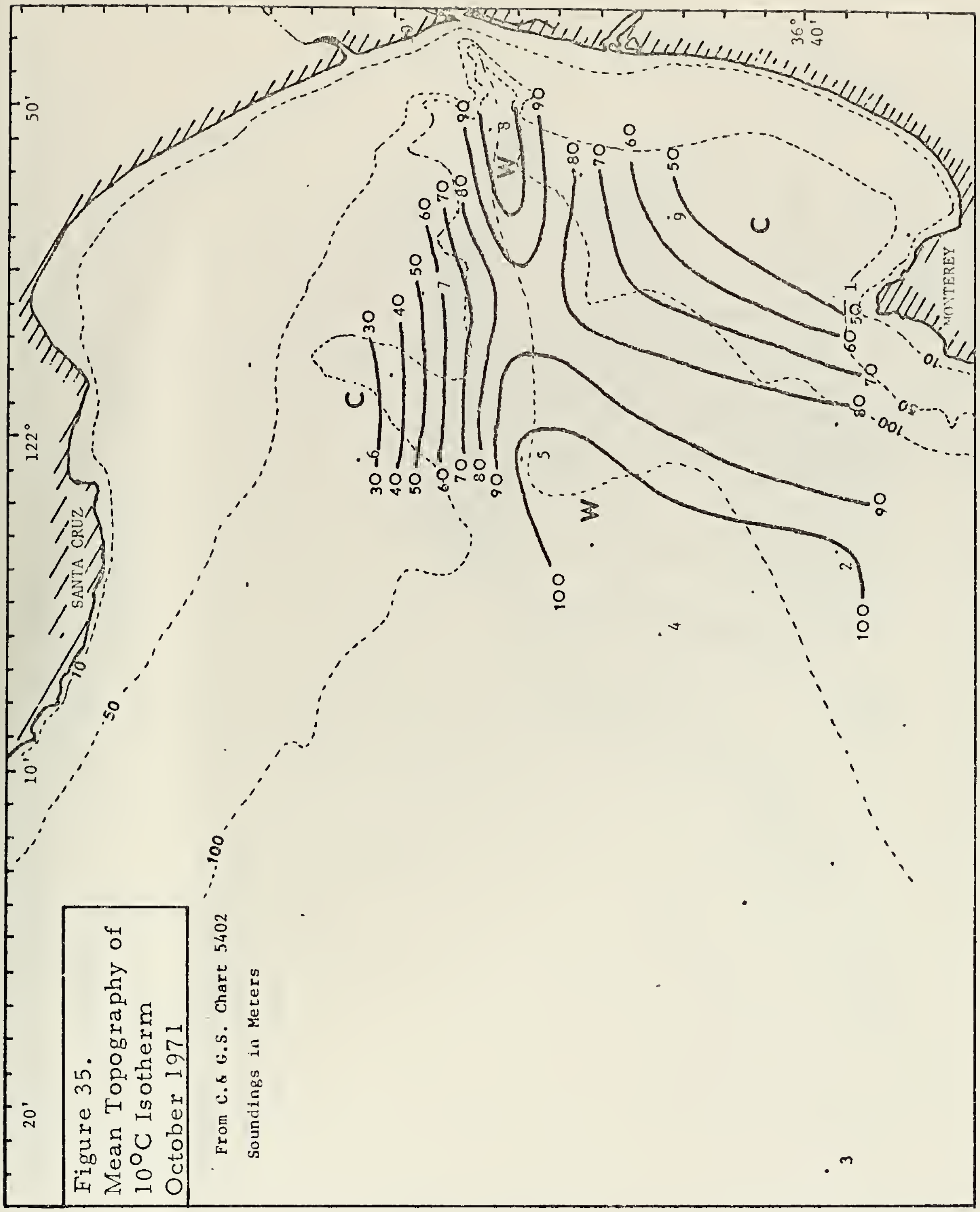


Figure 35.
Mean Topography of
$10^{\circ}C$ Isotherm
October 1971

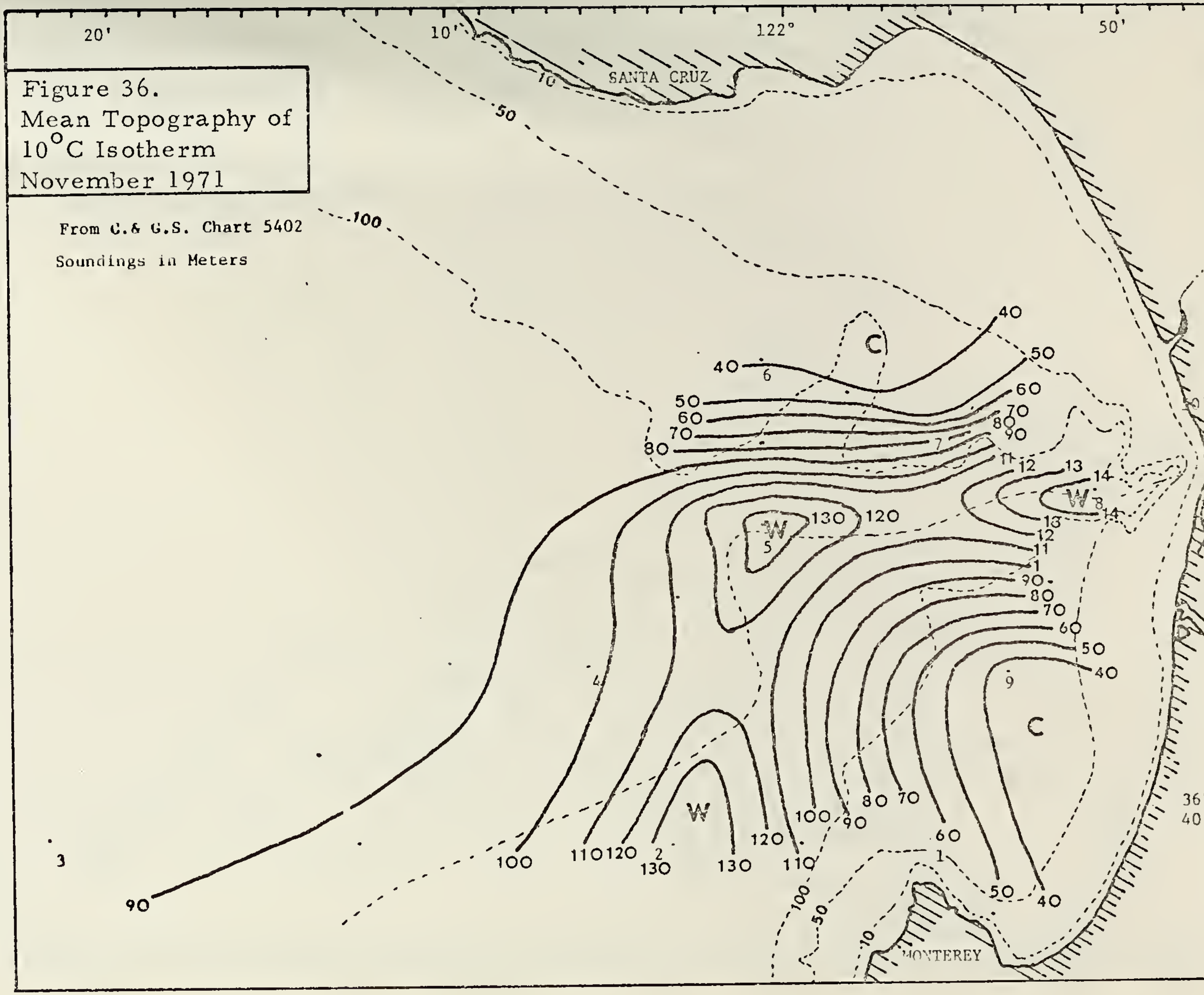


Figure 36.
Mean Topography of
$10^{\circ}C$ Isotherm
November 1971

From C.& G.S. Chart 5402

Soundings in Meters

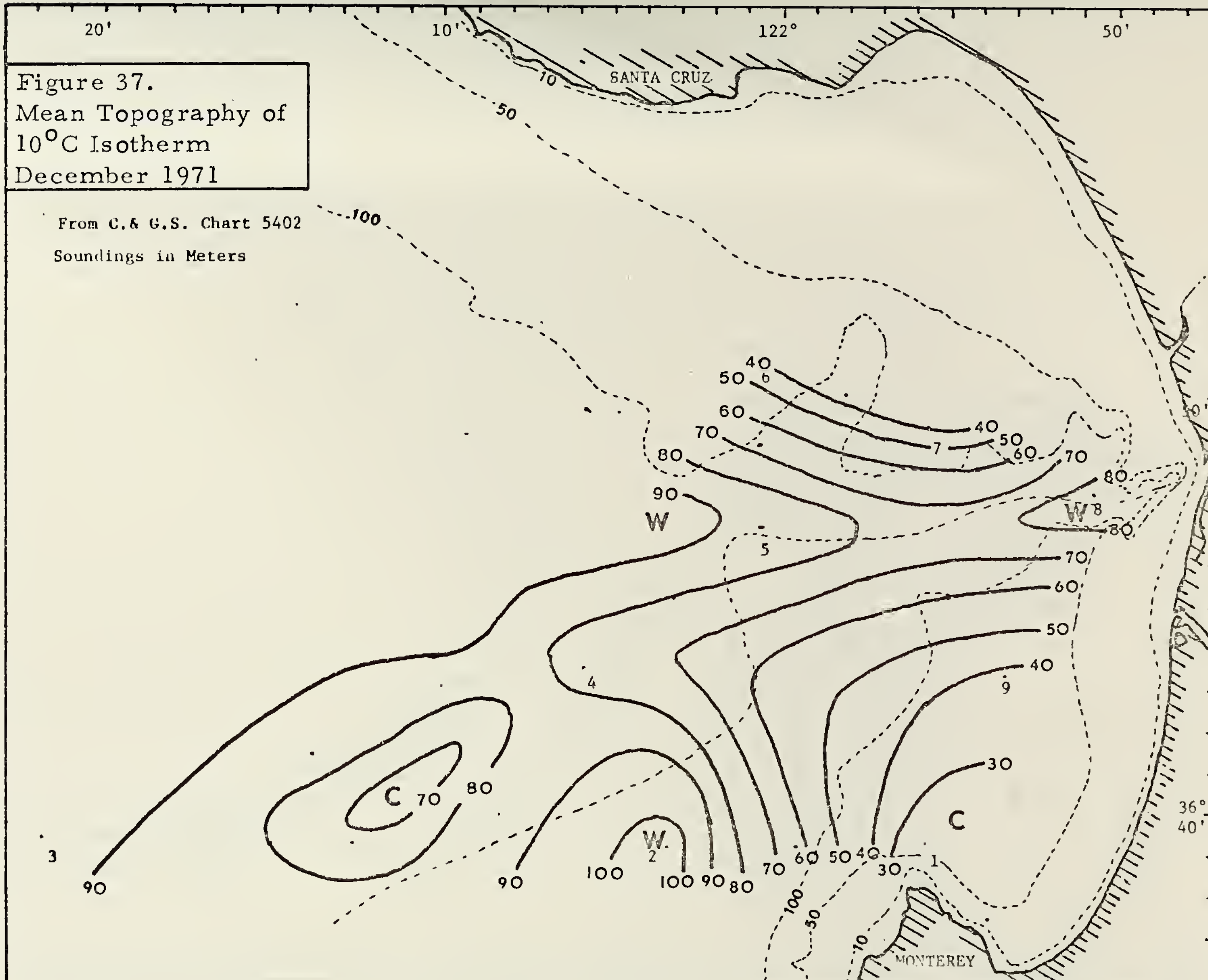


Figure 37.
Mean Topography of
$10^{\circ}C$ Isotherm
December 1971

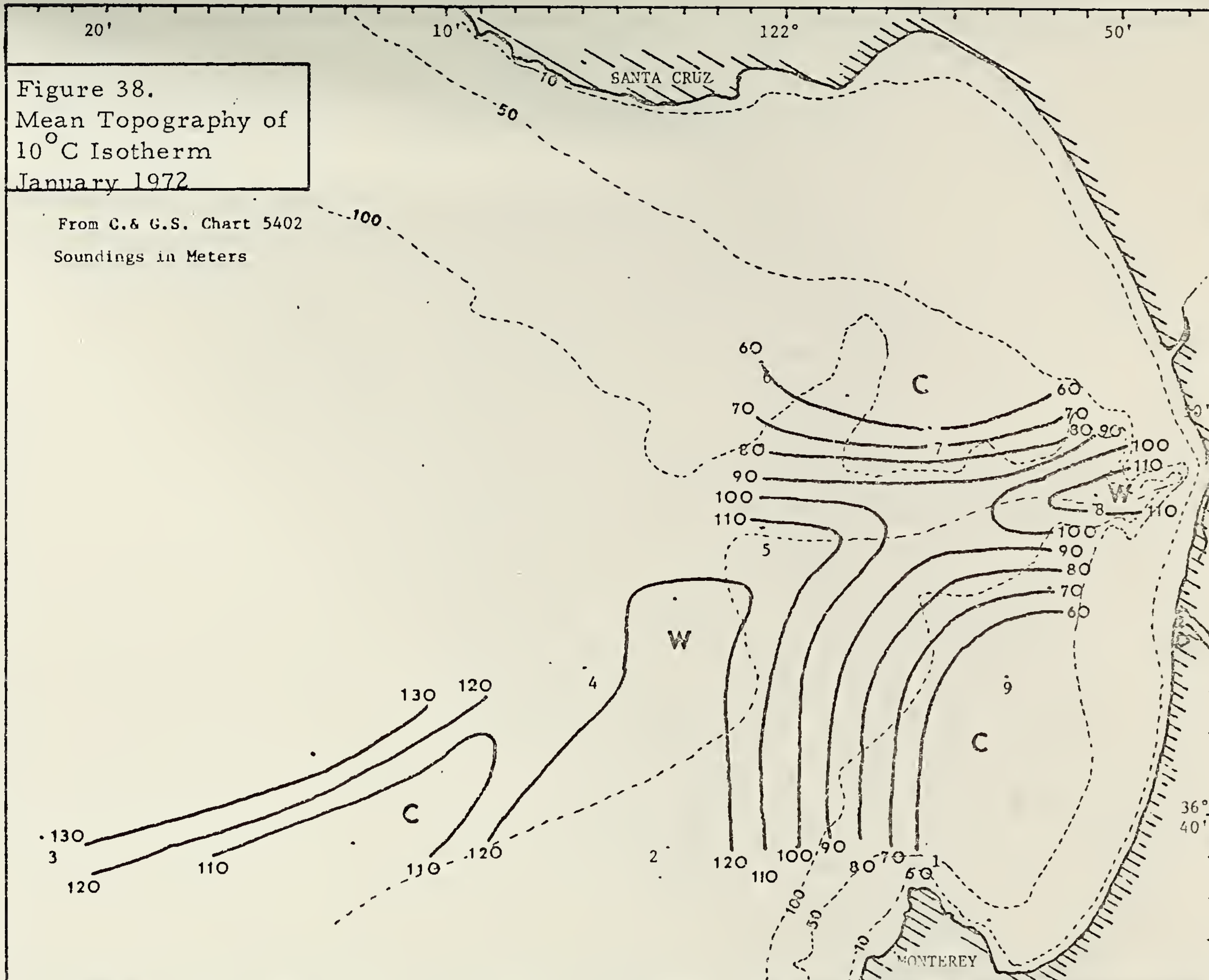


Figure 38.
Mean Topography of
10°C Isotherm
January 1972

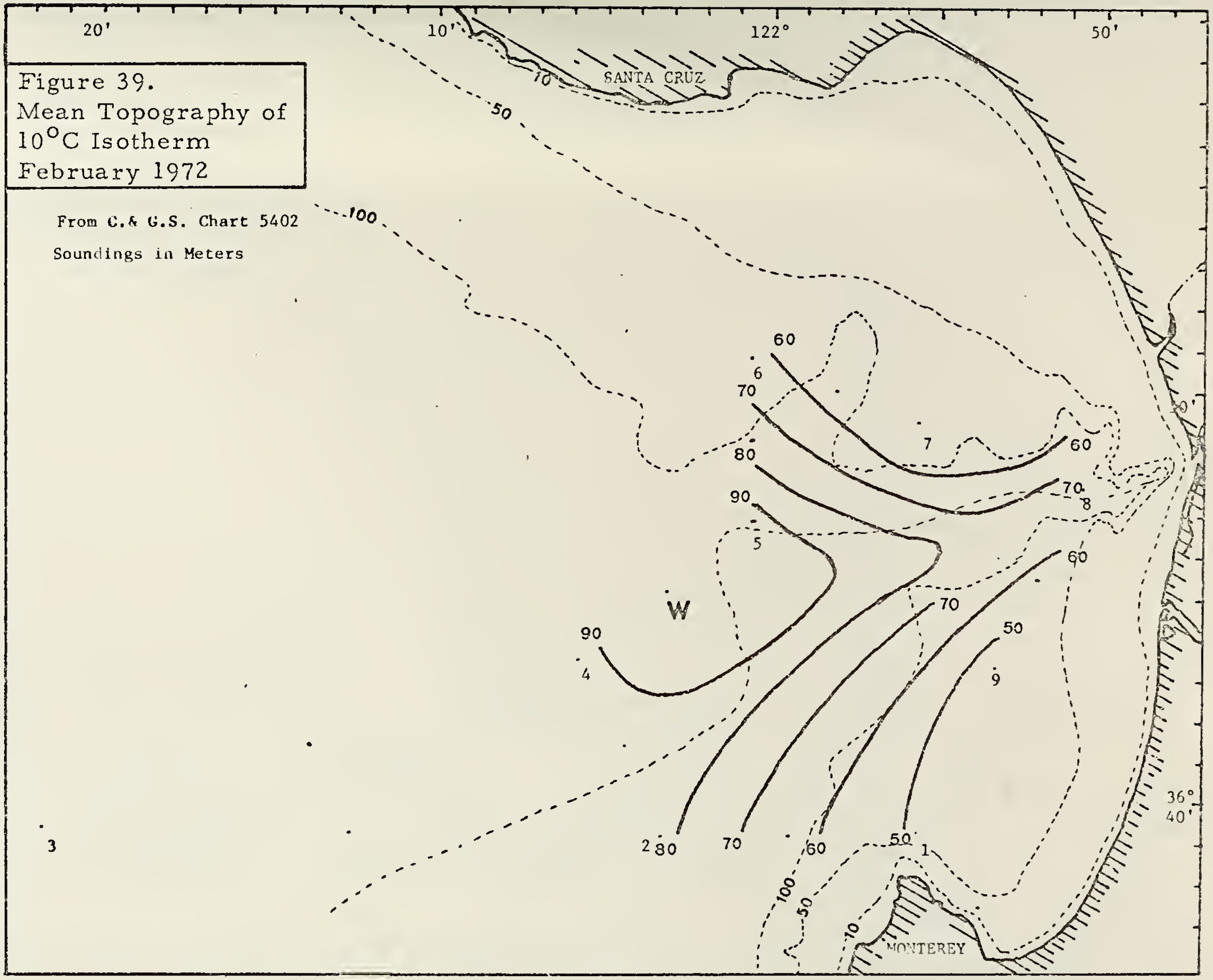


Figure 39.
Mean Topography of
10°C Isotherm
February 1972

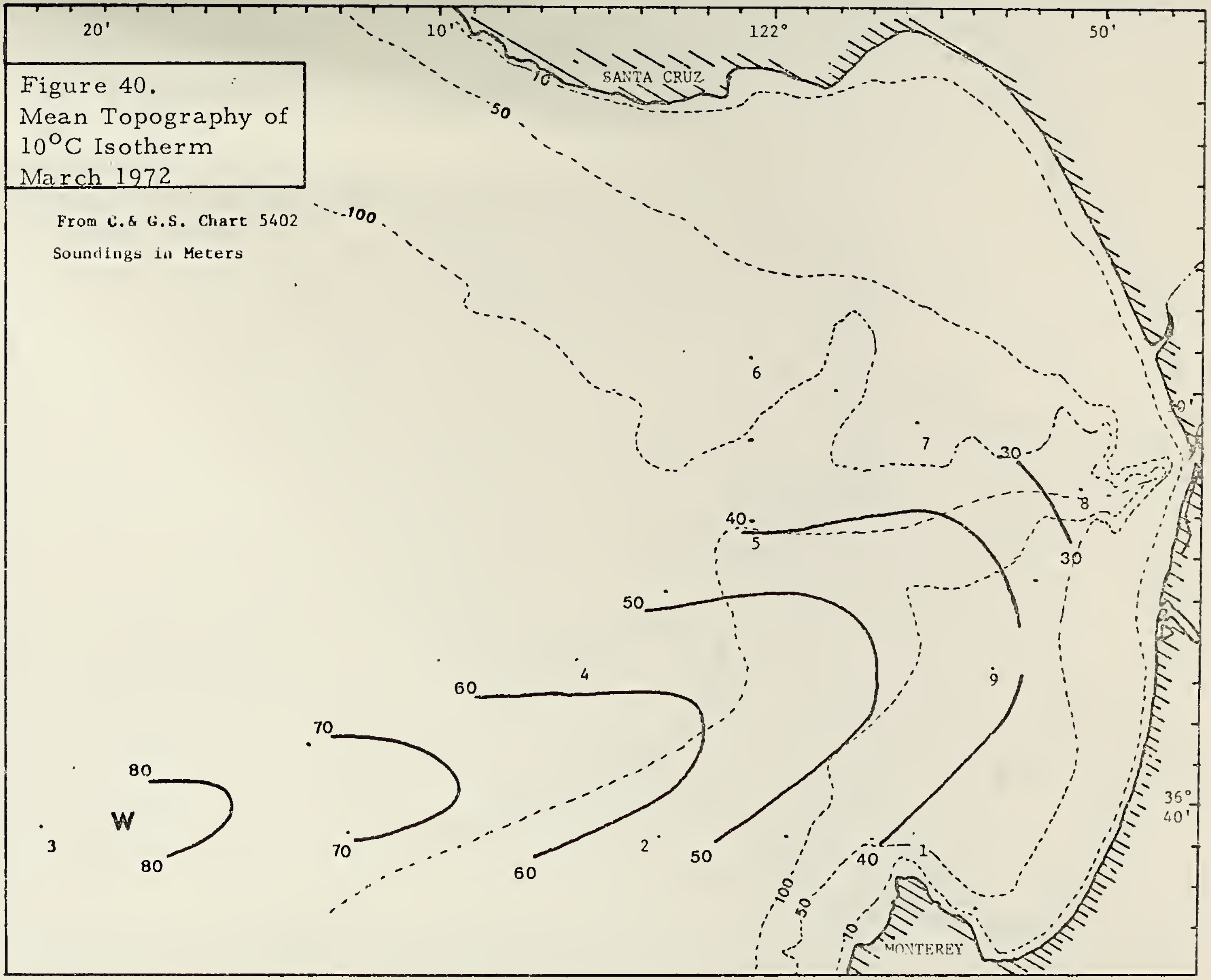


Figure 40.
Mean Topography of
$10^{\circ}C$ Isotherm
March 1972

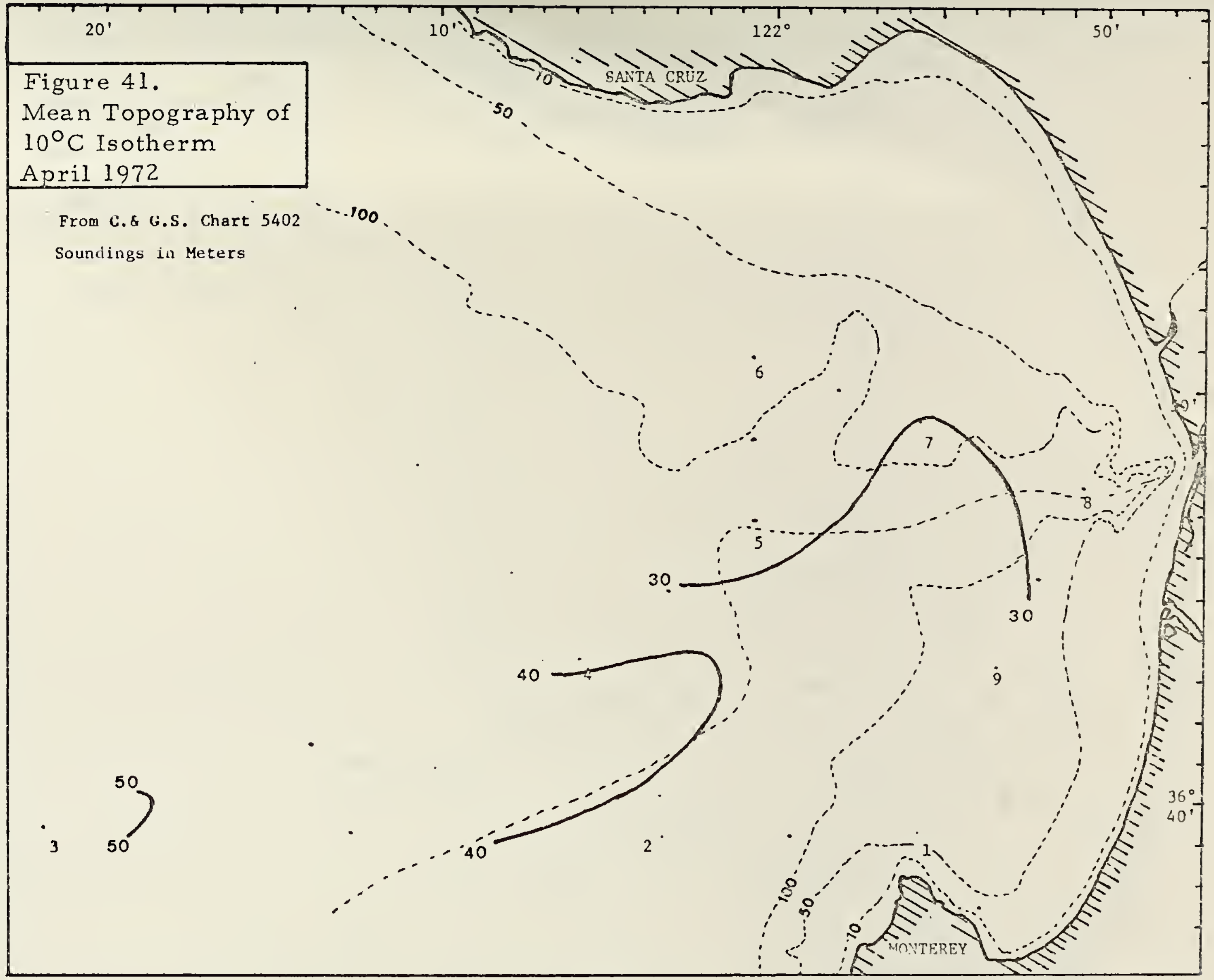


Figure 41.
Mean Topography of
10°C Isotherm
April 1972

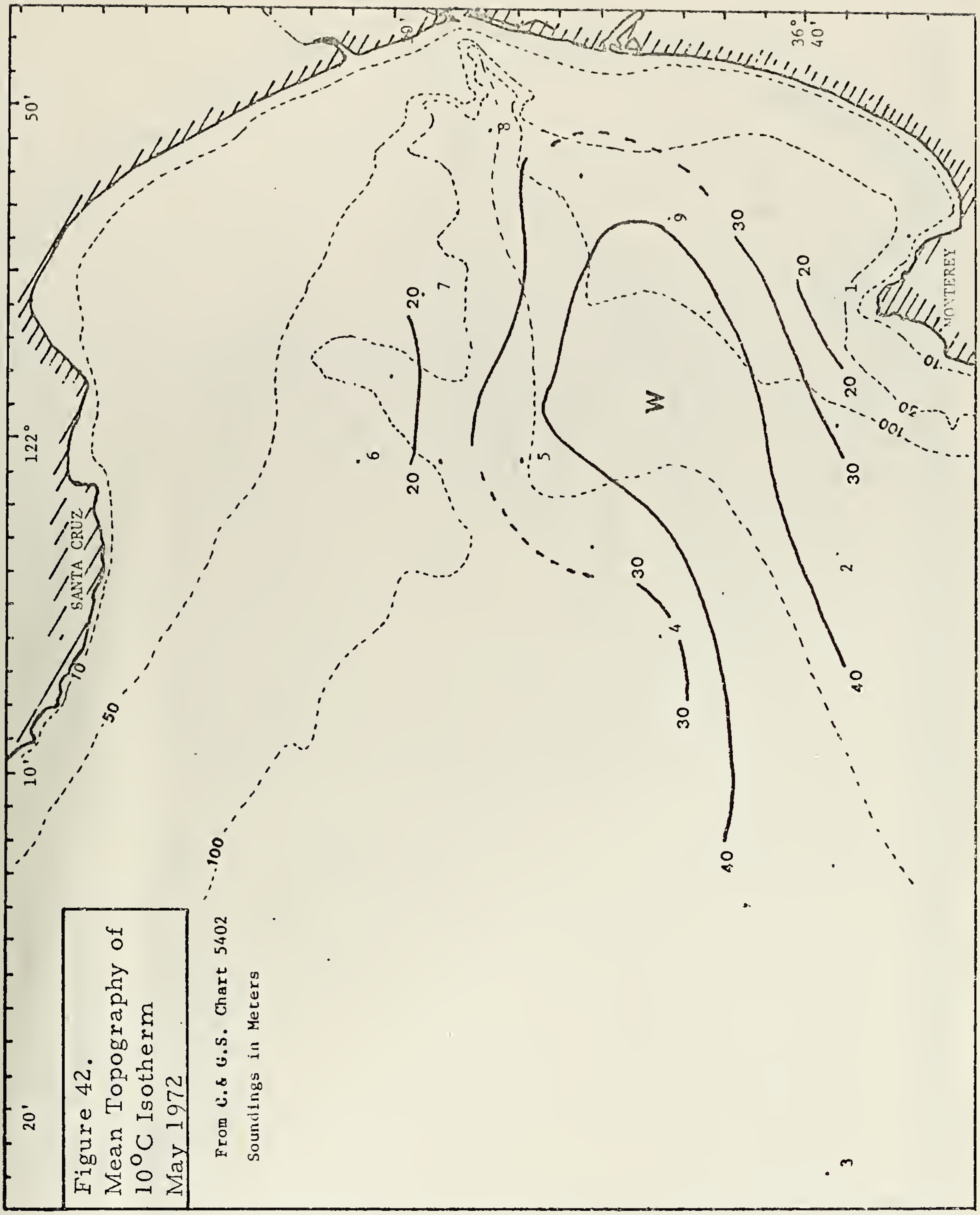


Figure 42.
Mean Topography of
10°C Isotherm
May 1972

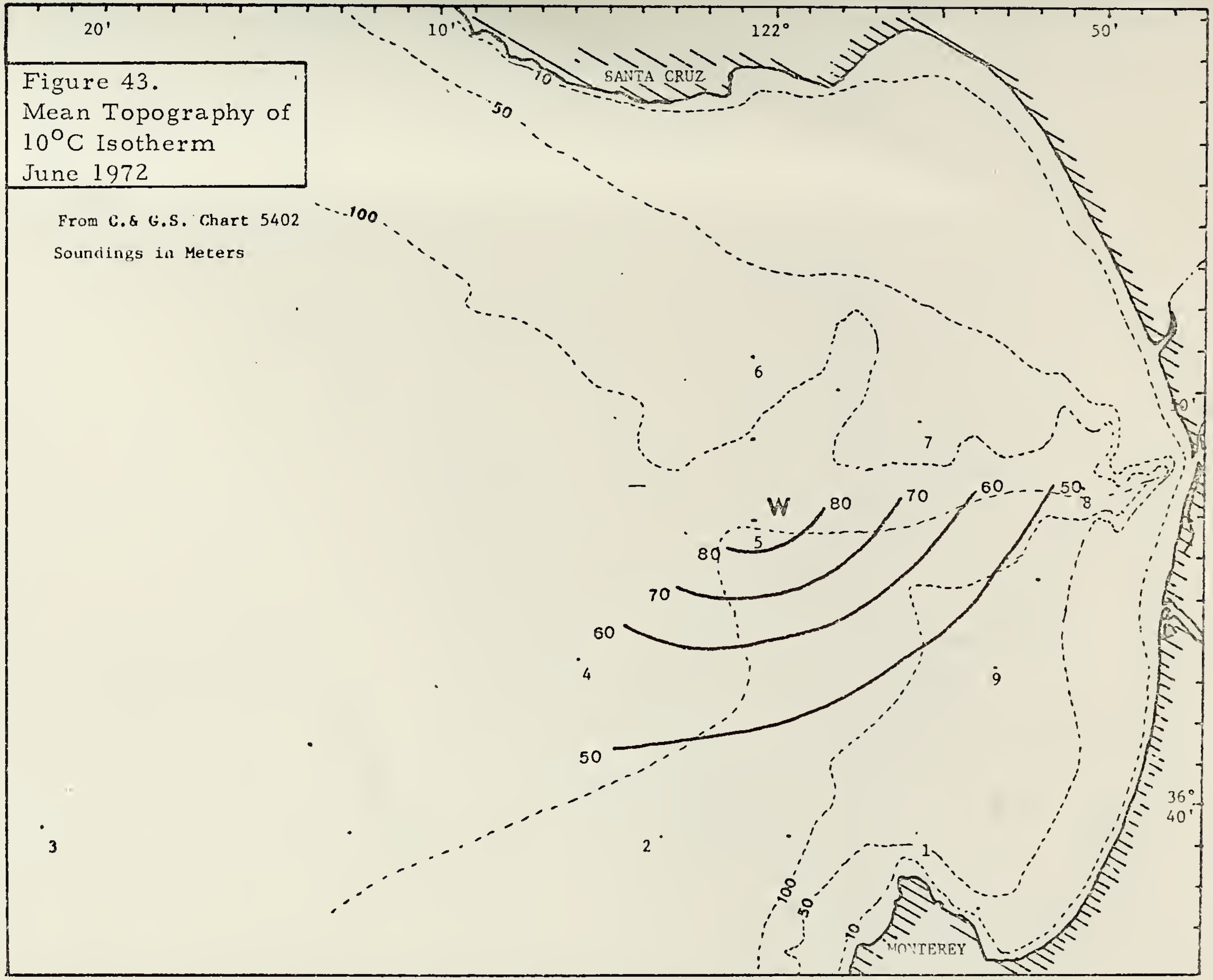


Figure 43.
Mean Topography of
$10^{O}C$ Isotherm
June 1972

From C.& G.S. Chart 5402

Soundings in Meters

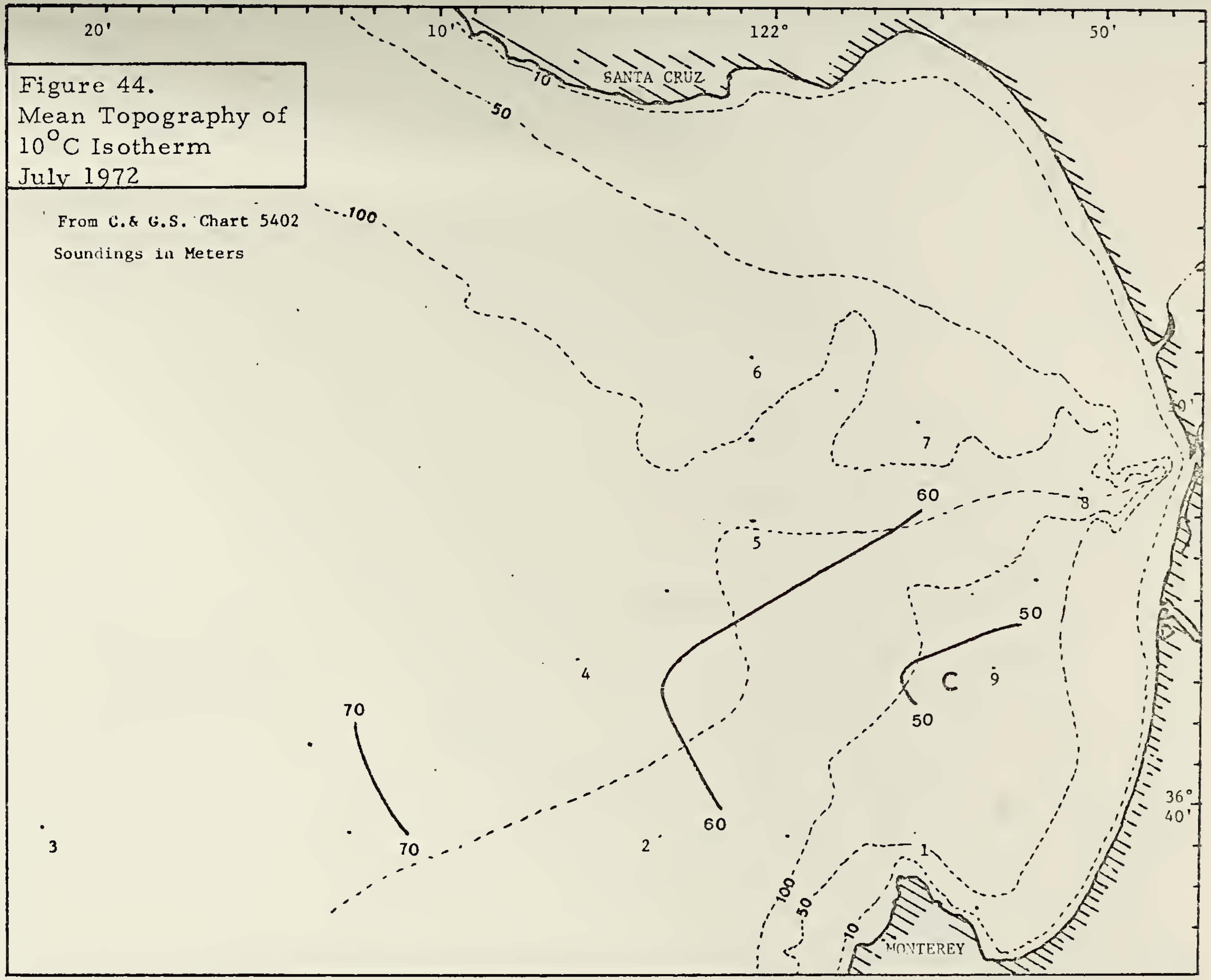


Figure 44.
Mean Topography of
$10^{\circ}C$ Isotherm
July 1972

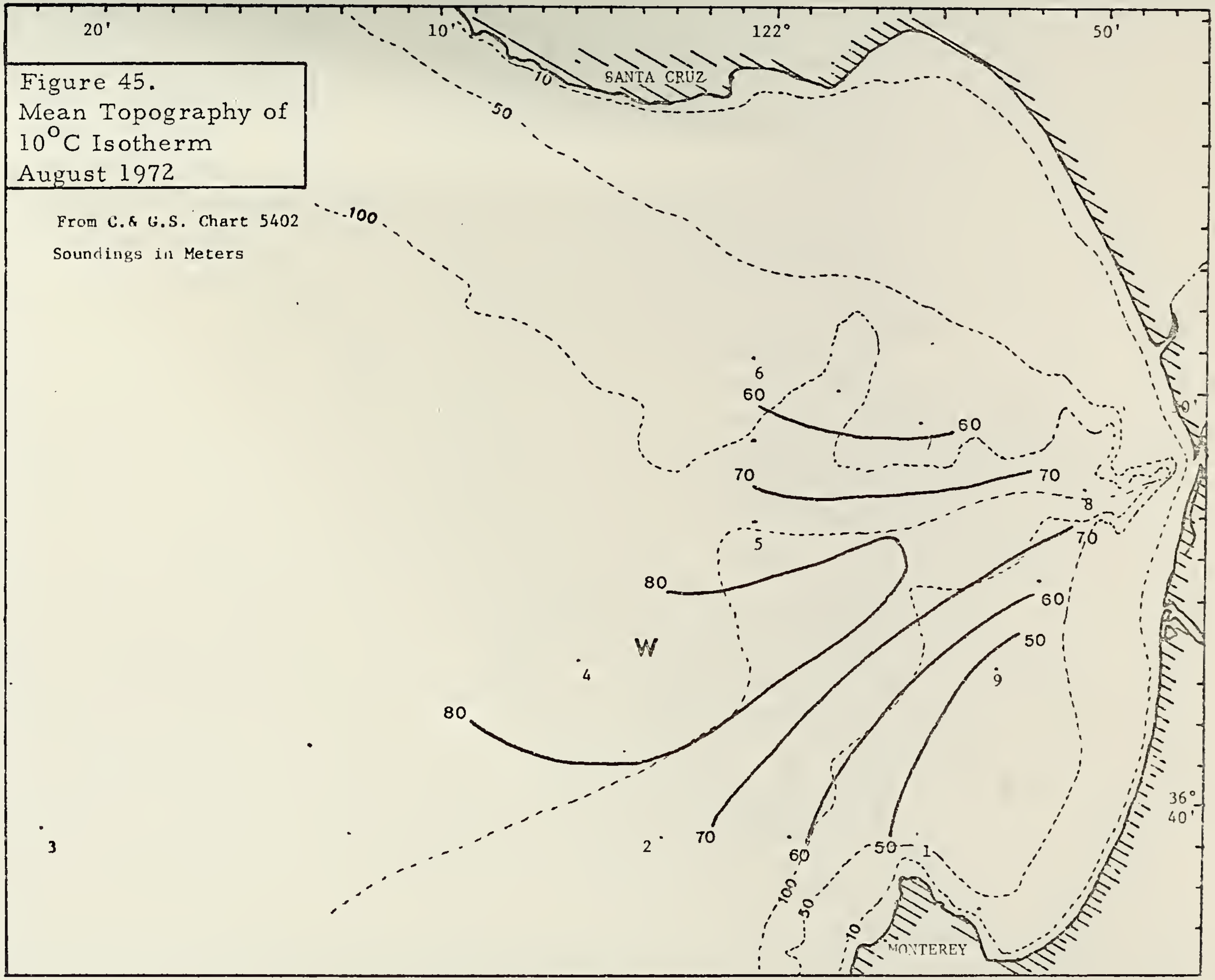


Figure 45.
Mean Topography of
$10^{o}C$ Isotherm
August 1972

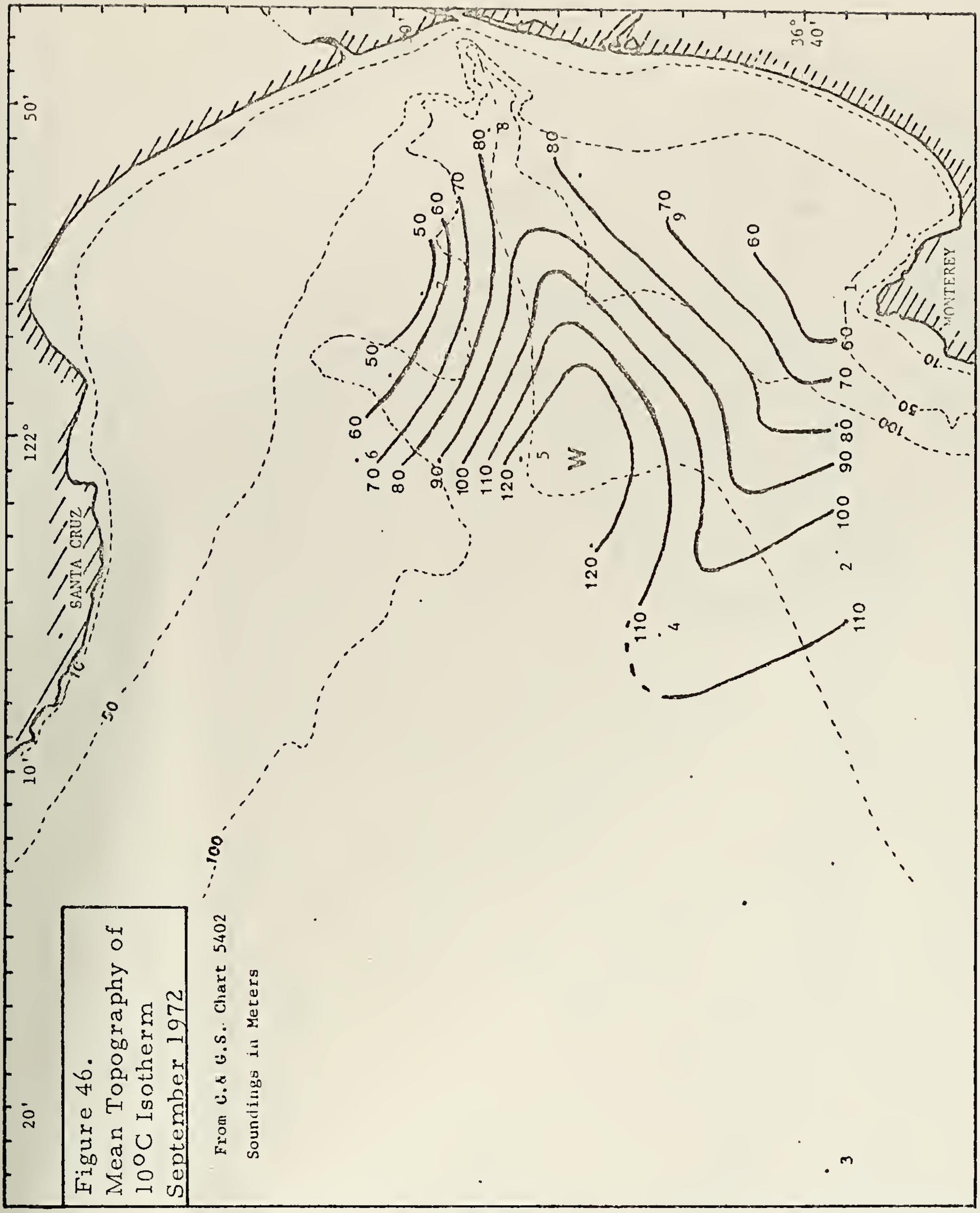


Figure 46.
Mean Topography of
$10^{o}C$ Isotherm
September 1972

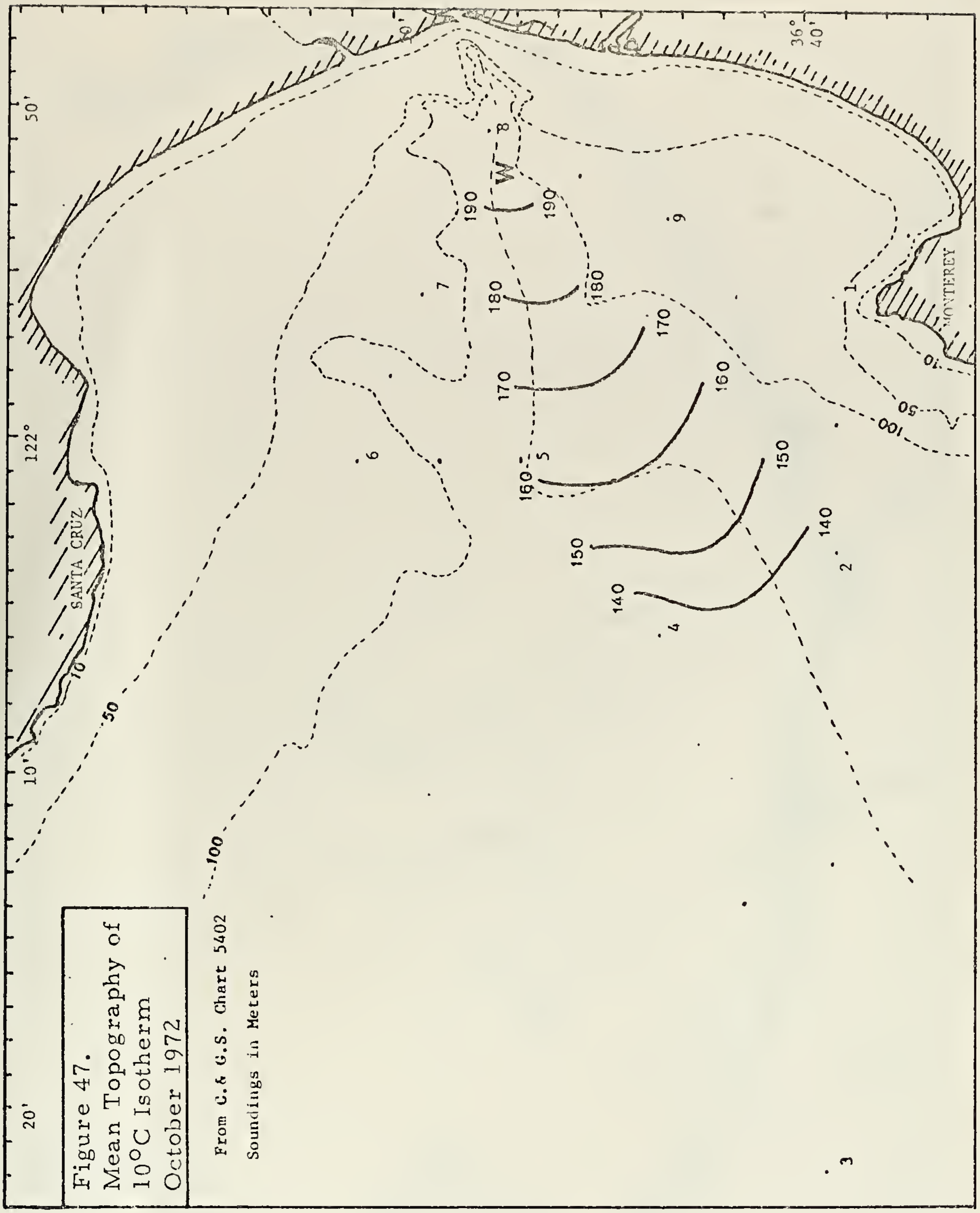


Figure 47.
Mean Topography of
10°C Isotherm
October 1972

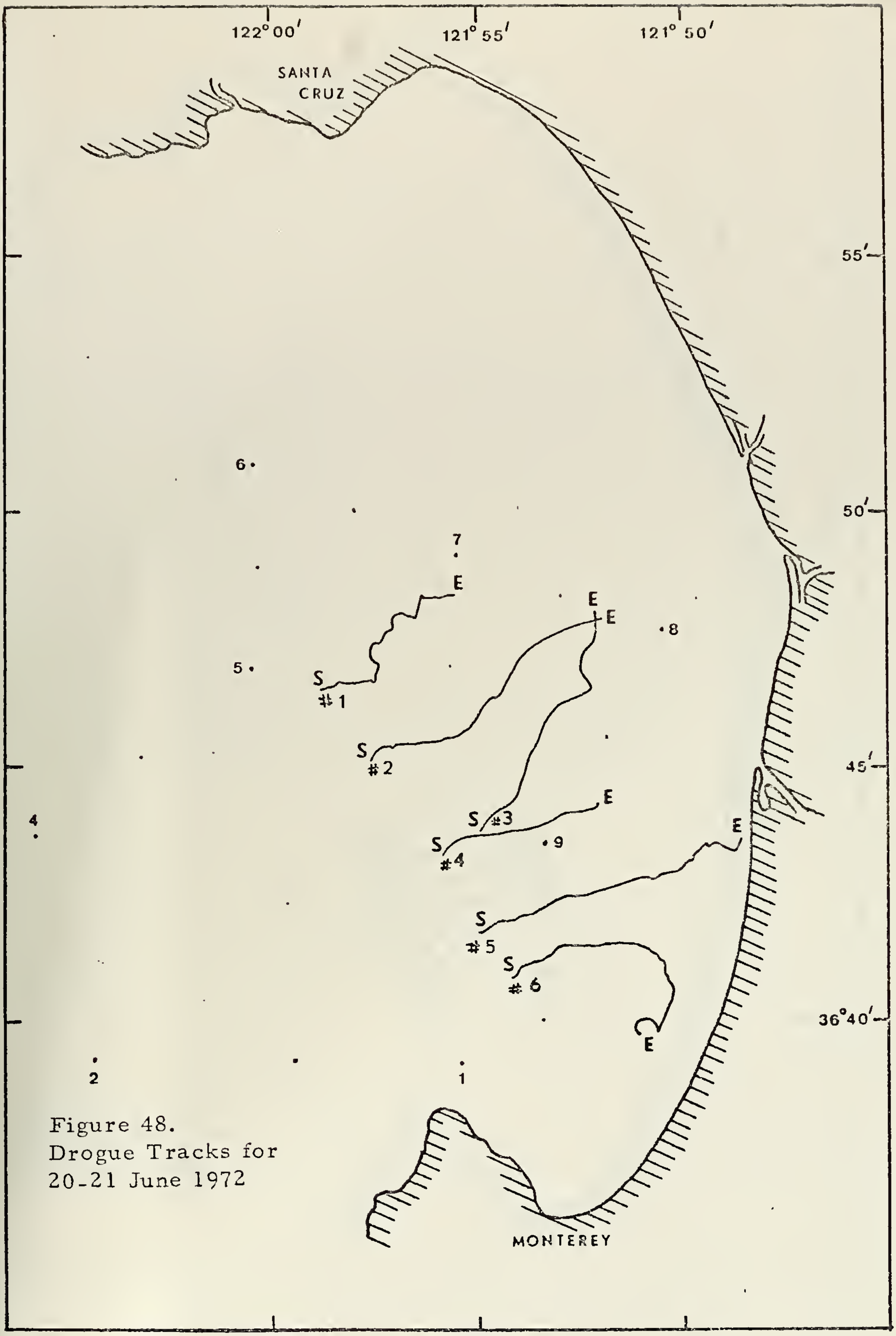


Figure 48.
Drogue Tracks for
20-21 June 1972

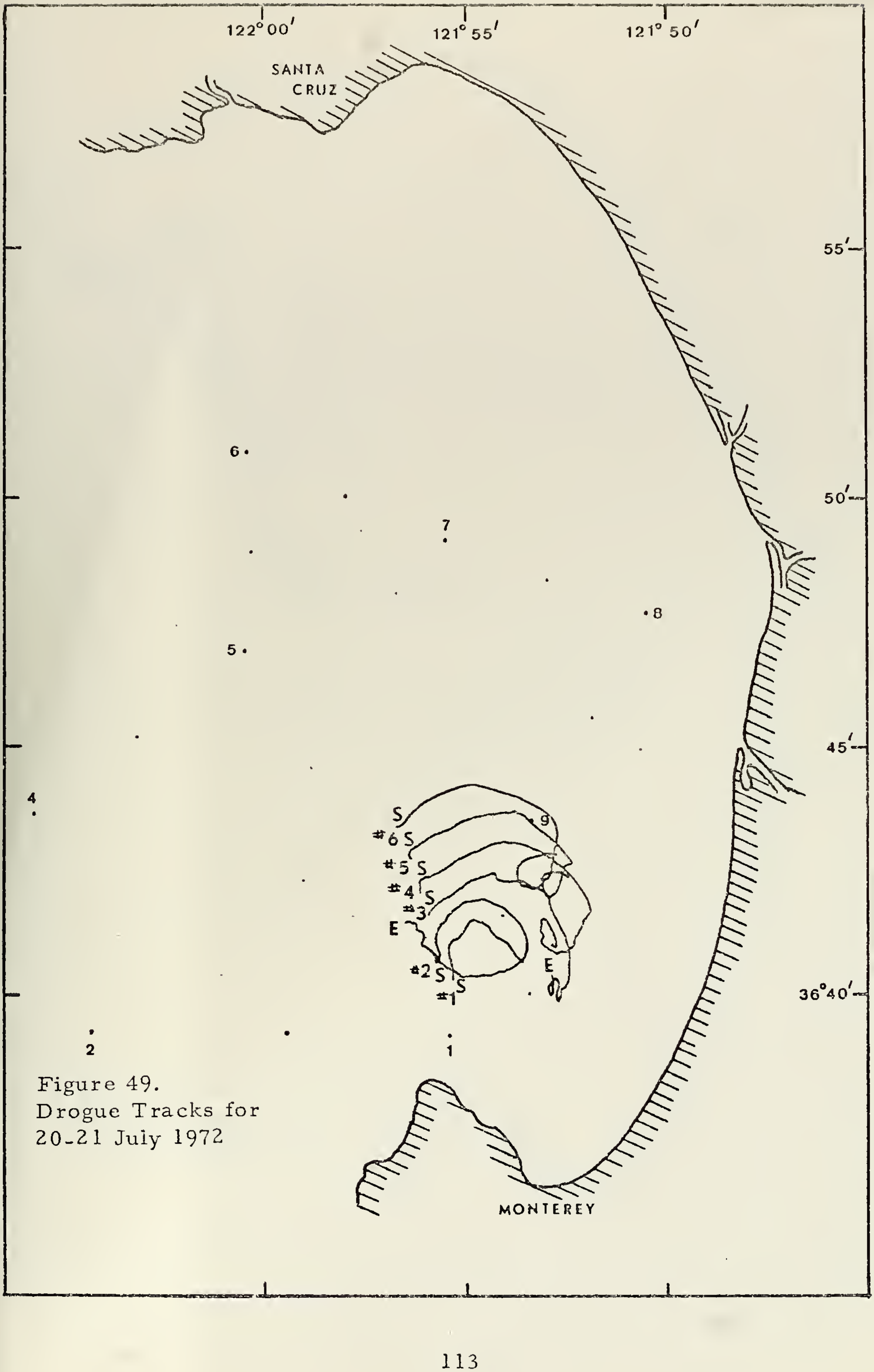


Figure 49.
Drogue Tracks for
20-21 July 1972

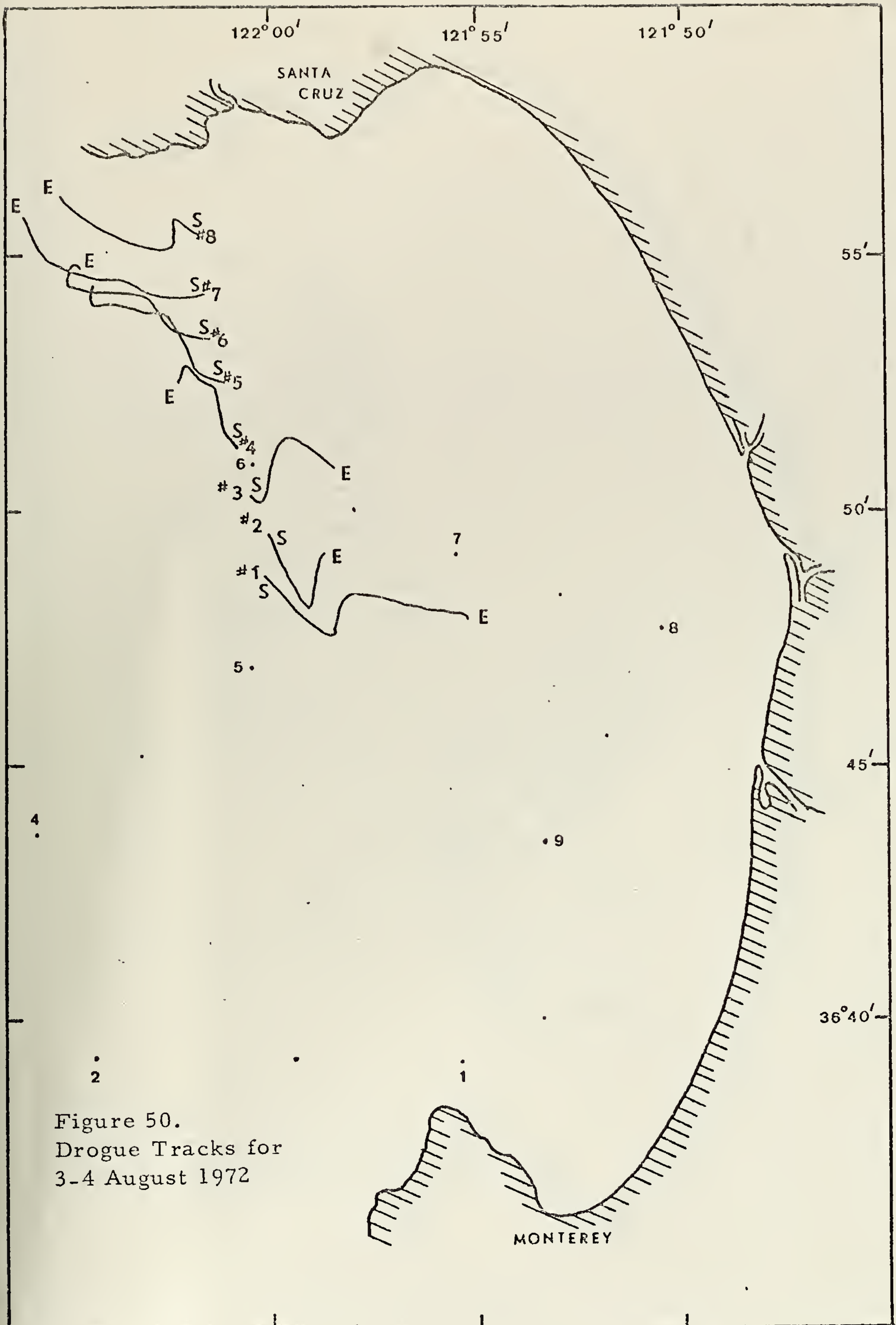


Figure 50.
Drogue Tracks for
3-4 August 1972

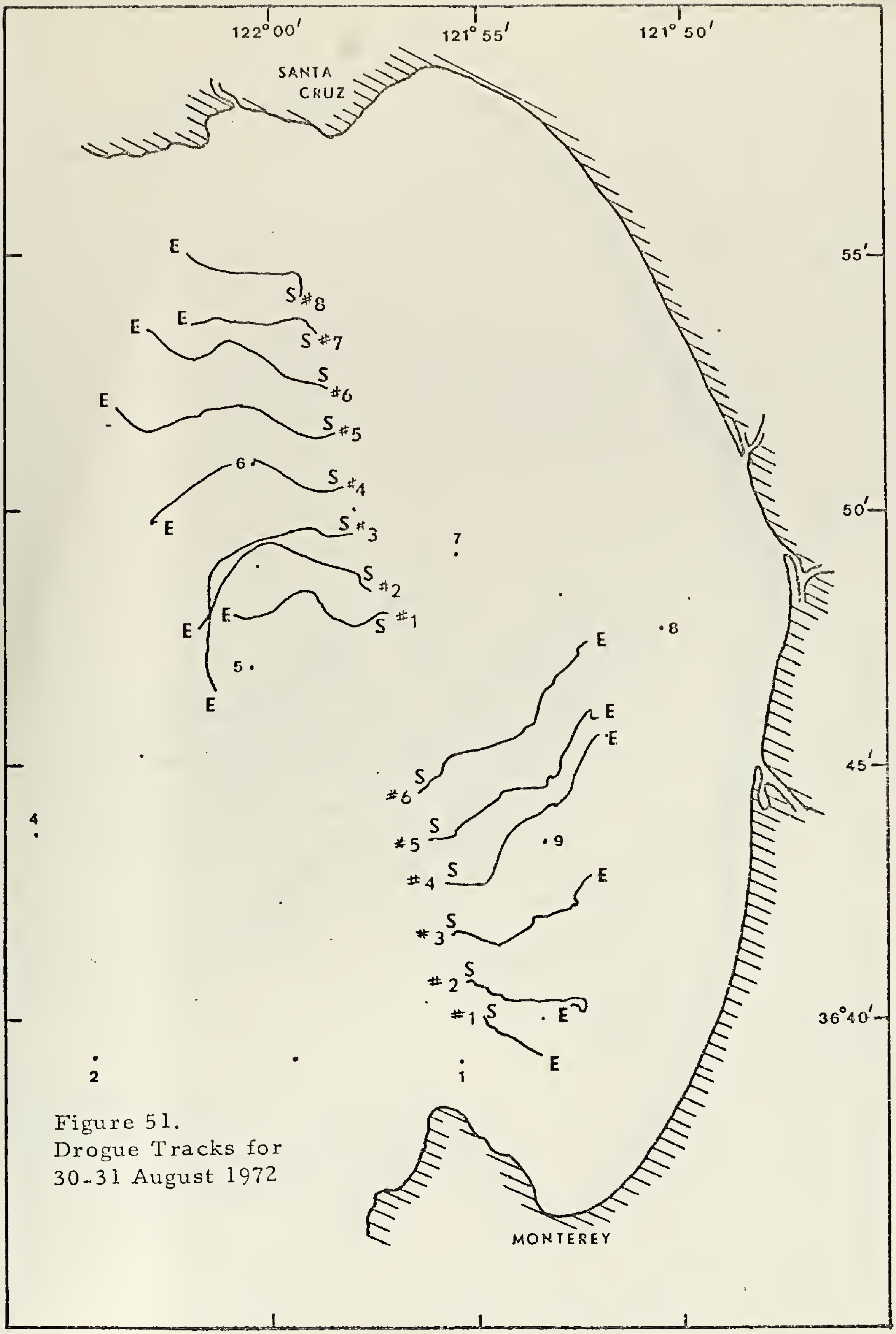


Figure 51.
Drogue Tracks for
30-31 August 1972

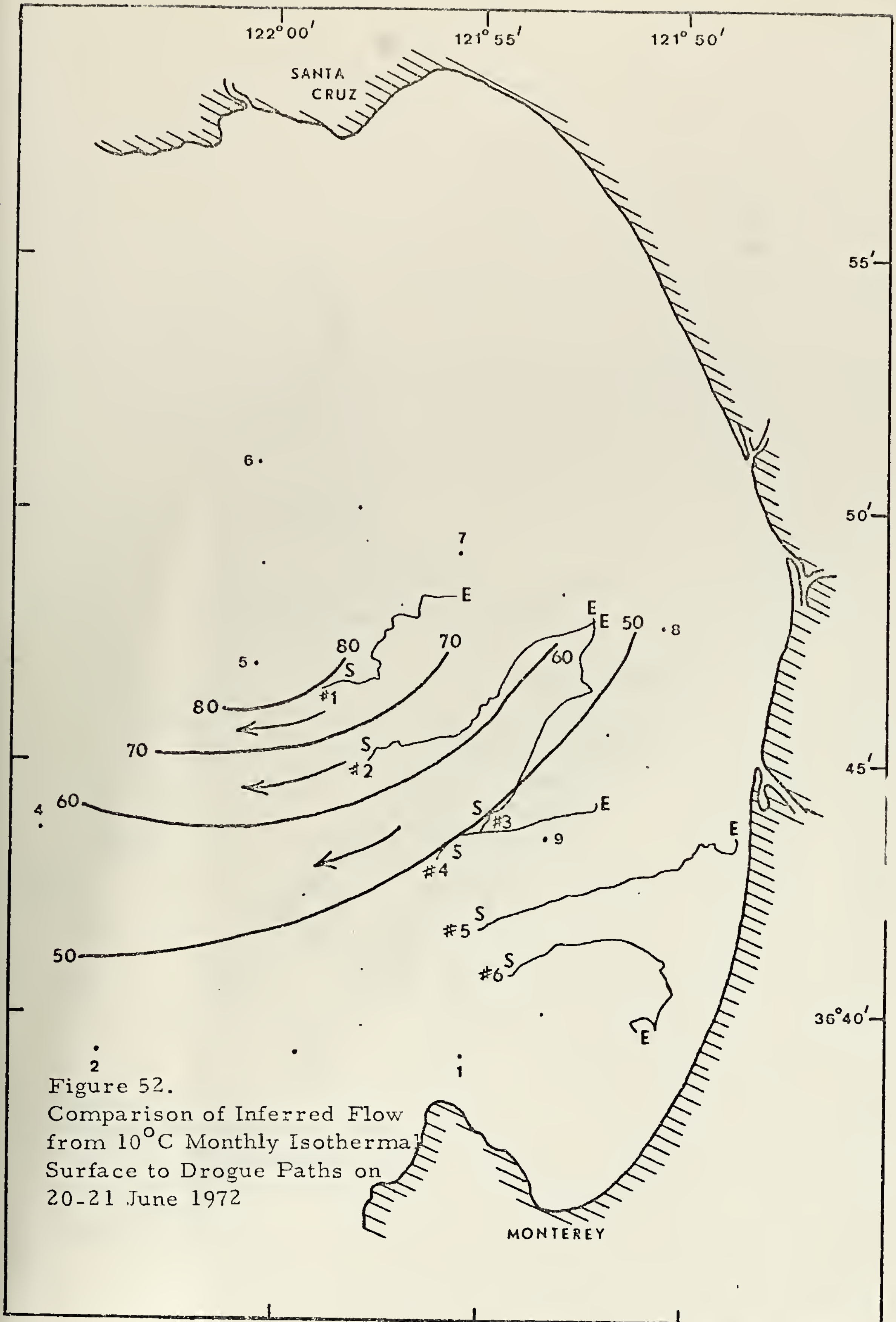


Figure 52.
Comparison of Inferred Flow from 10°C Monthly Isothermal Surface to Drogue Paths on 20-21 June 1972

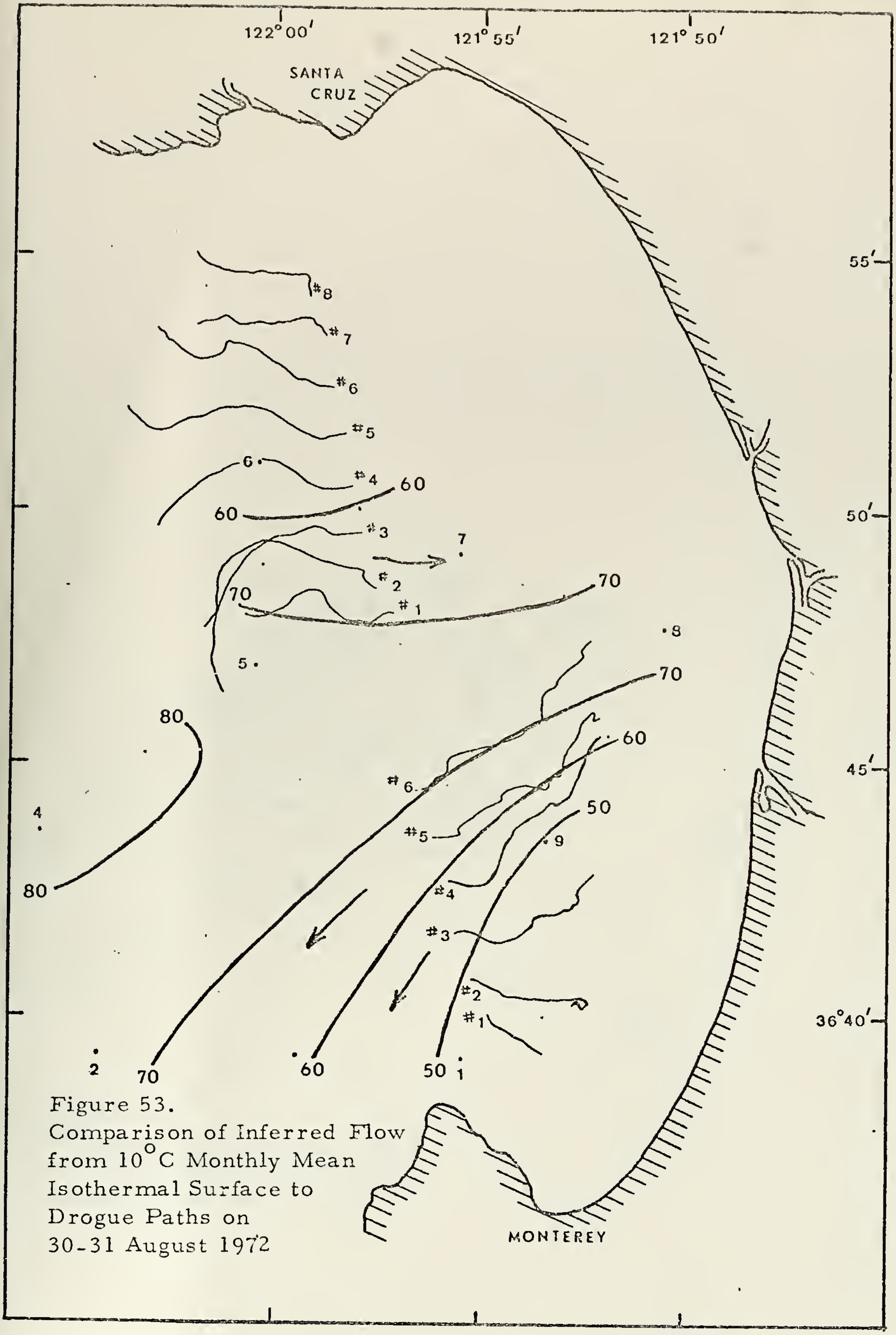


Figure 53.
Comparison of Inferred Flow from 10°C Monthly Mean Isothermal Surface to Drogue Paths on 30-31 August 1972

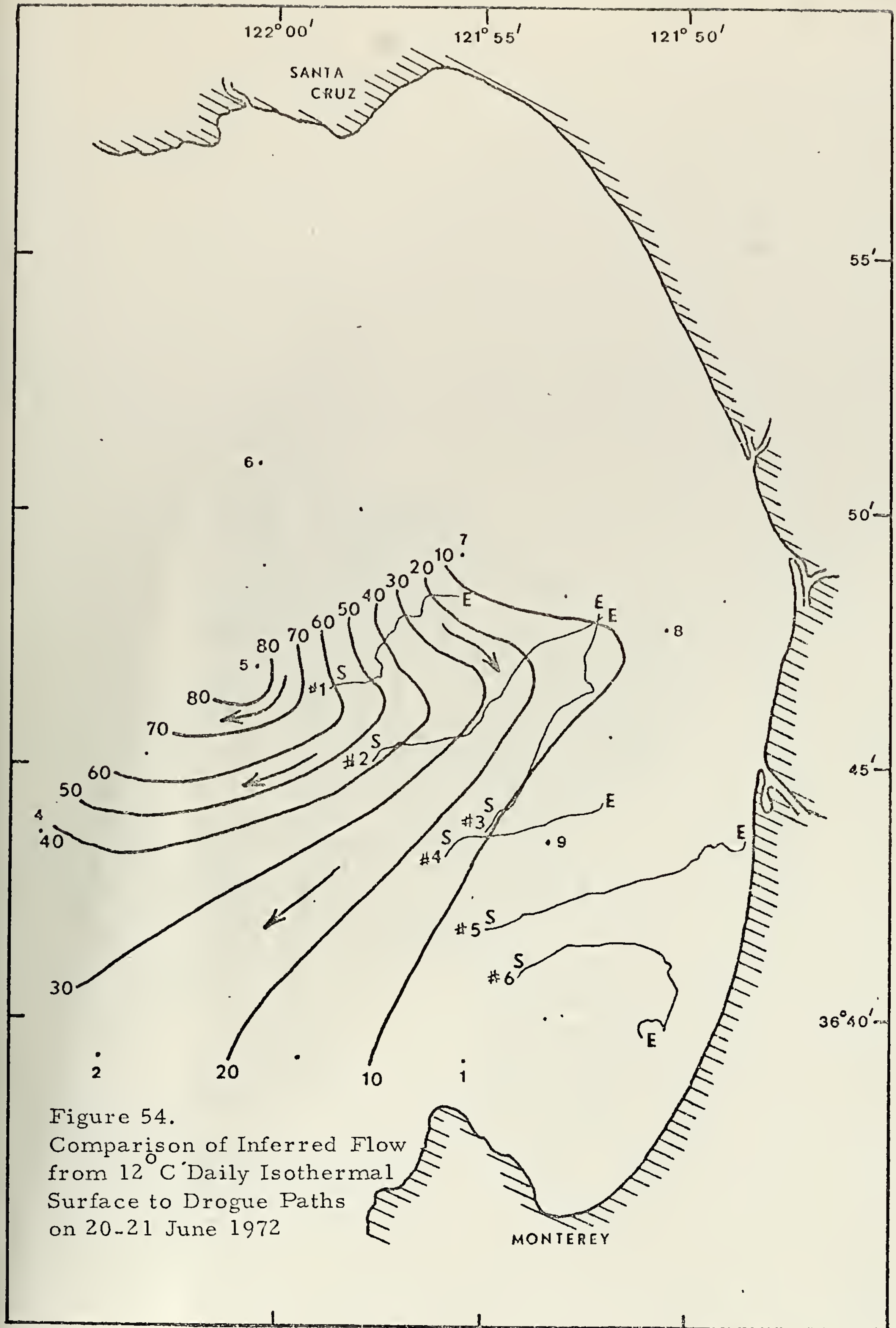


Figure 54.
Comparison of Inferred Flow from 12 °C Daily Isothermal Surface to Drogue Paths on 20-21 June 1972

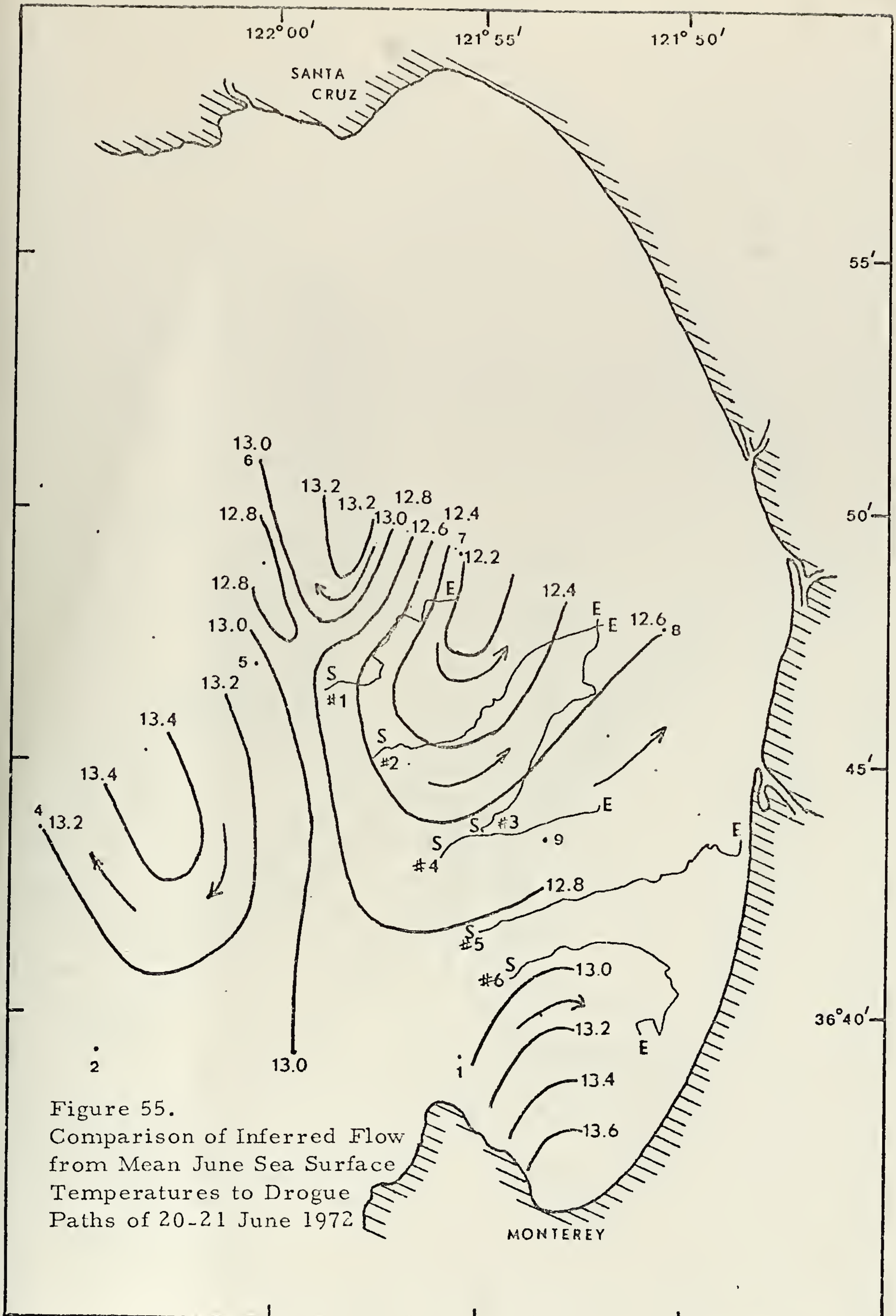


Figure 55.
Comparison of Inferred Flow from Mean June Sea Surface Temperatures to Drogue Paths of 20-21 June 1972

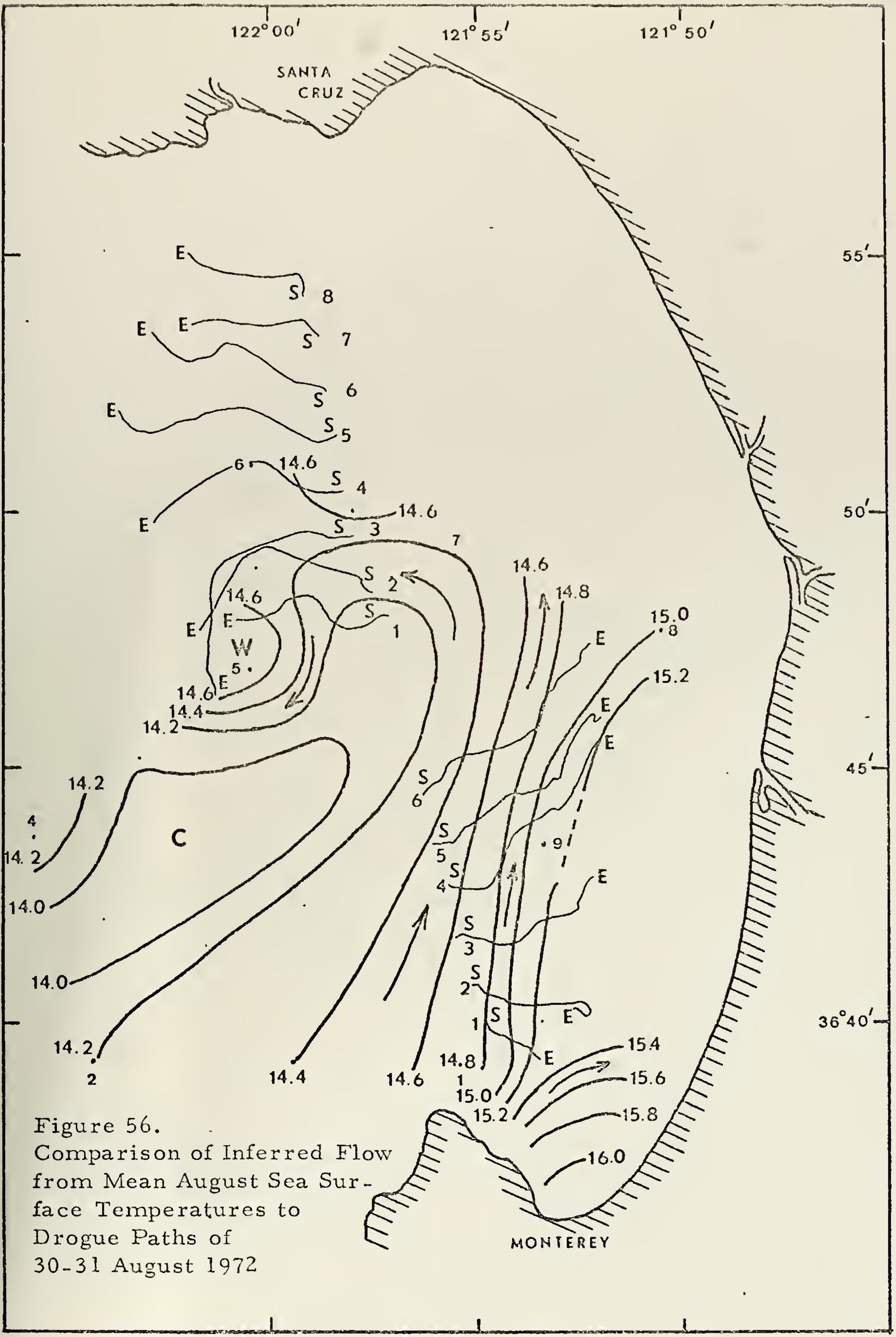


Figure 56.
Comparison of Inferred Flow from Mean August Sea Surface Temperatures to Drogue Paths of 30-31 August 1972

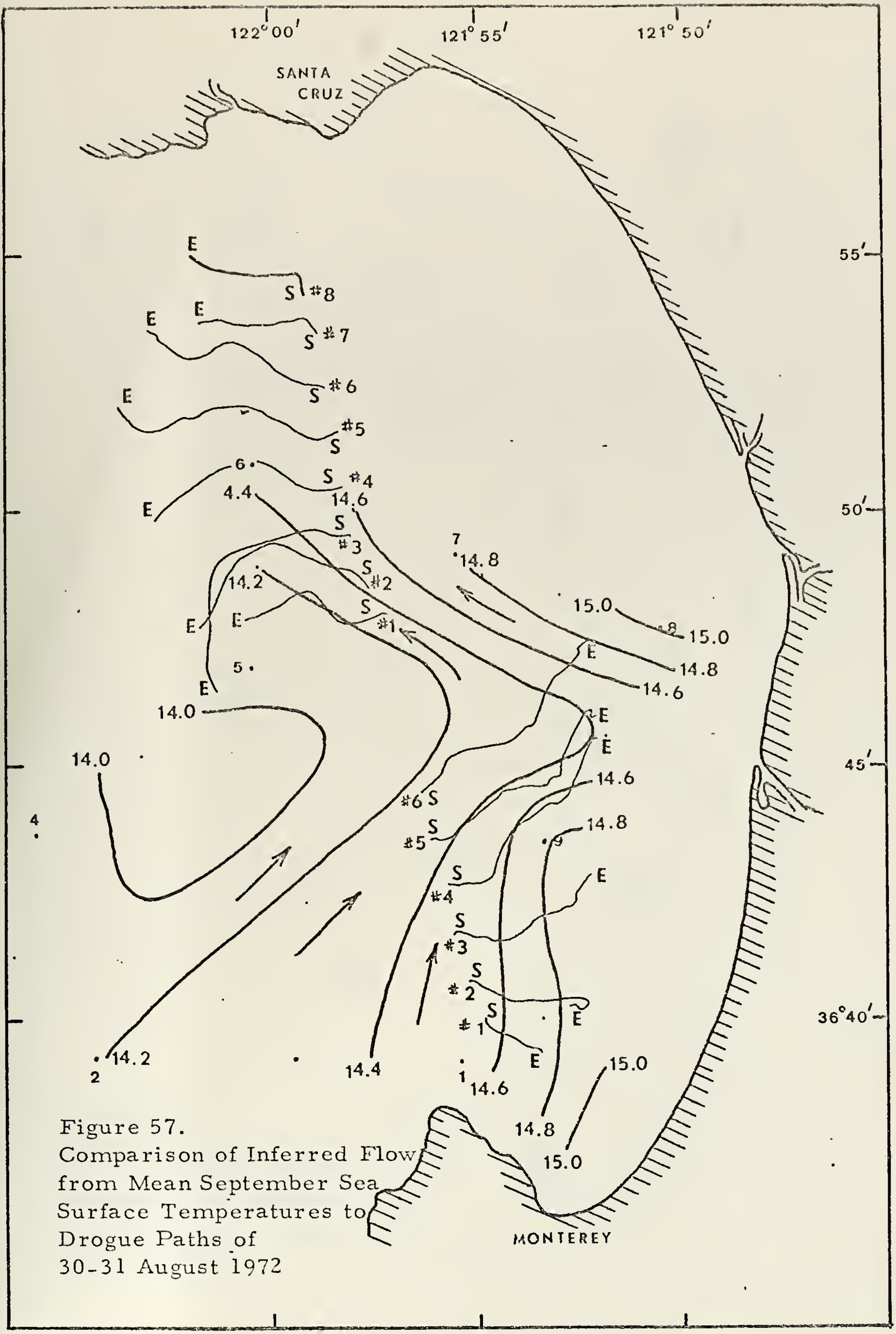


Figure 57.
Comparison of Inferred Flow from Mean September Sea Surface Temperatures to Drogue Paths of 30-31 August 1972

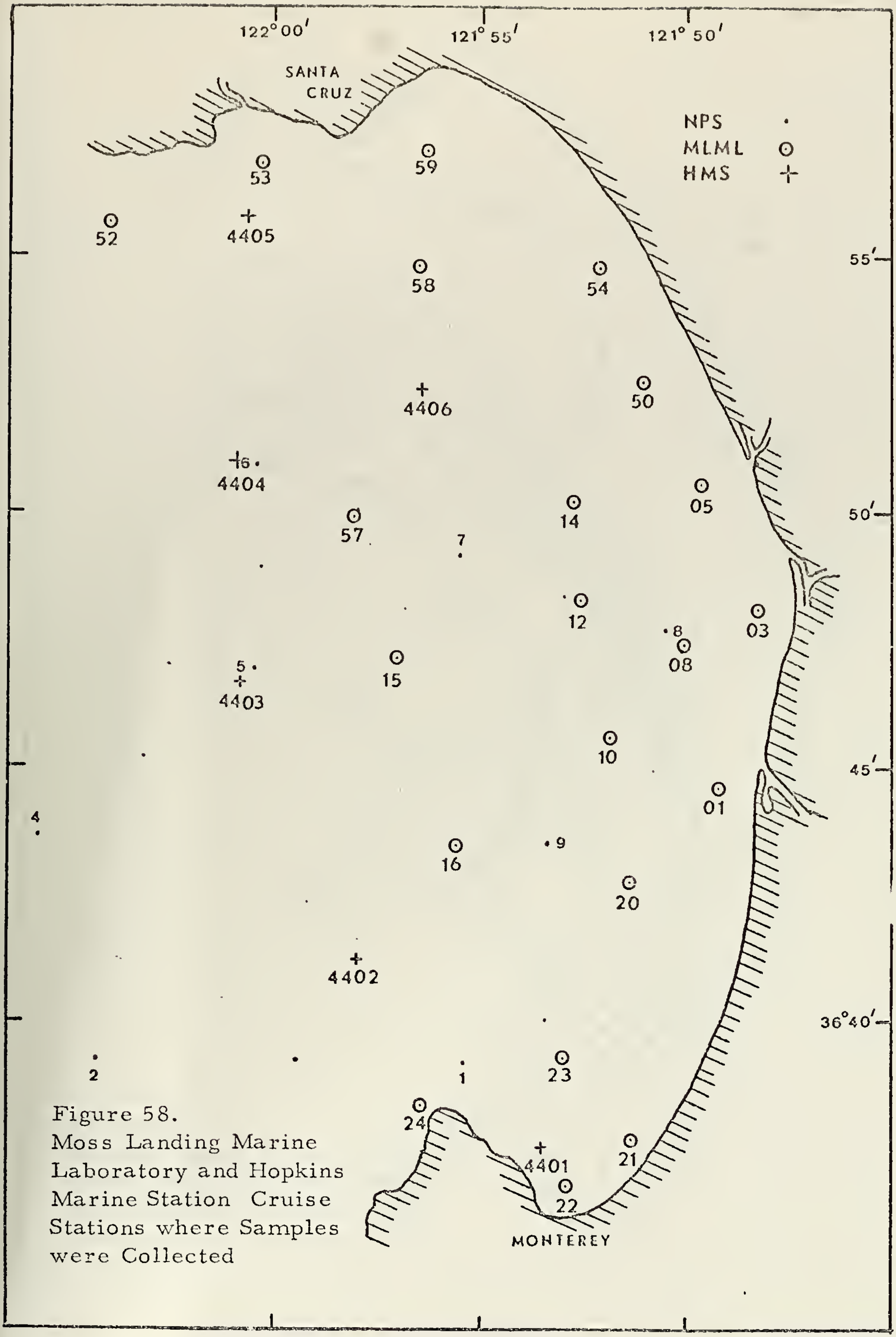


Figure 58.
Moss Landing Marine Laboratory and Hopkins Marine Station Cruise Stations where Samples were Collected

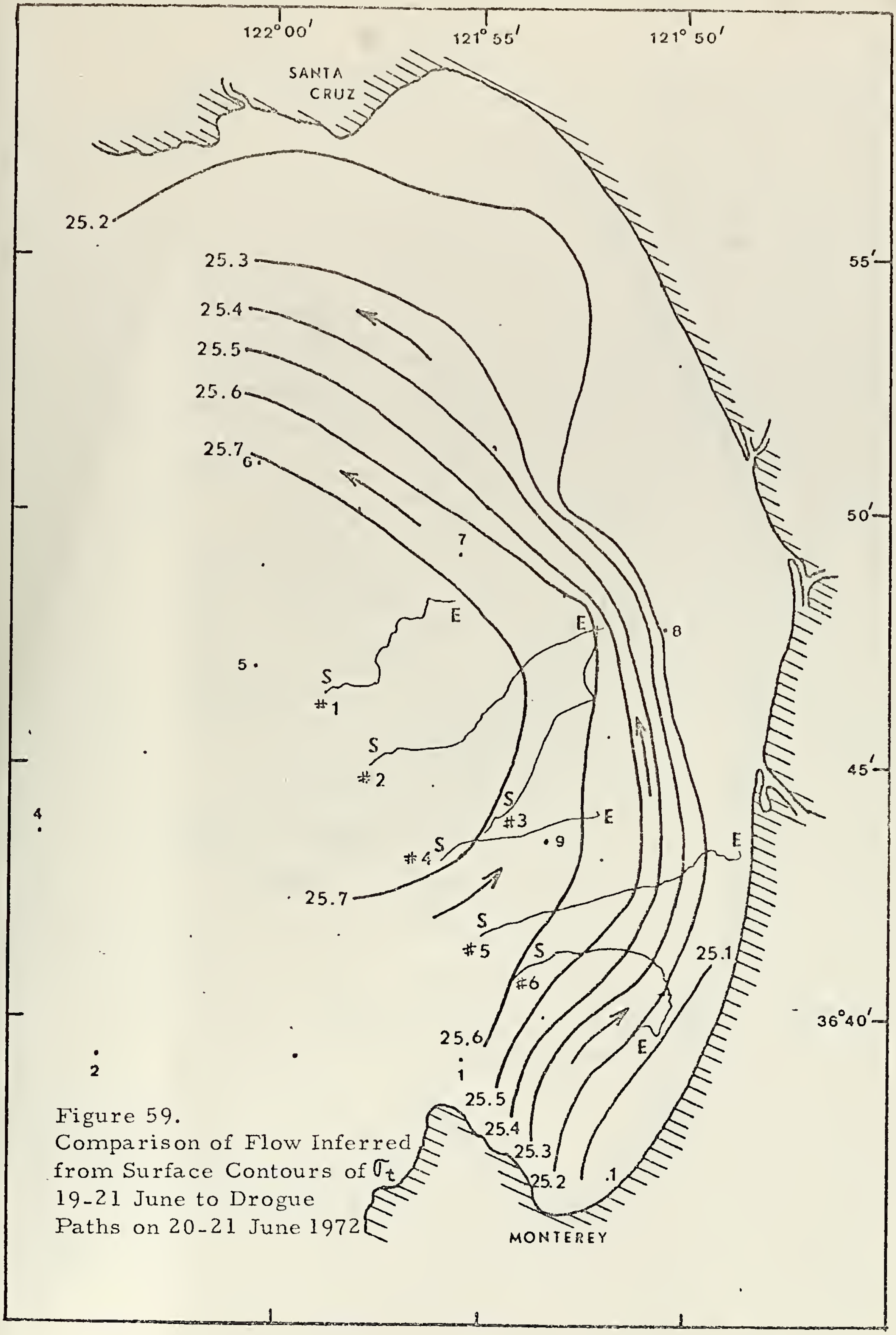


Figure 59.
Comparison of Flow Inferred from Surface Contours of σ_t 19-21 June to Drogue Paths on 20-21 June 1972

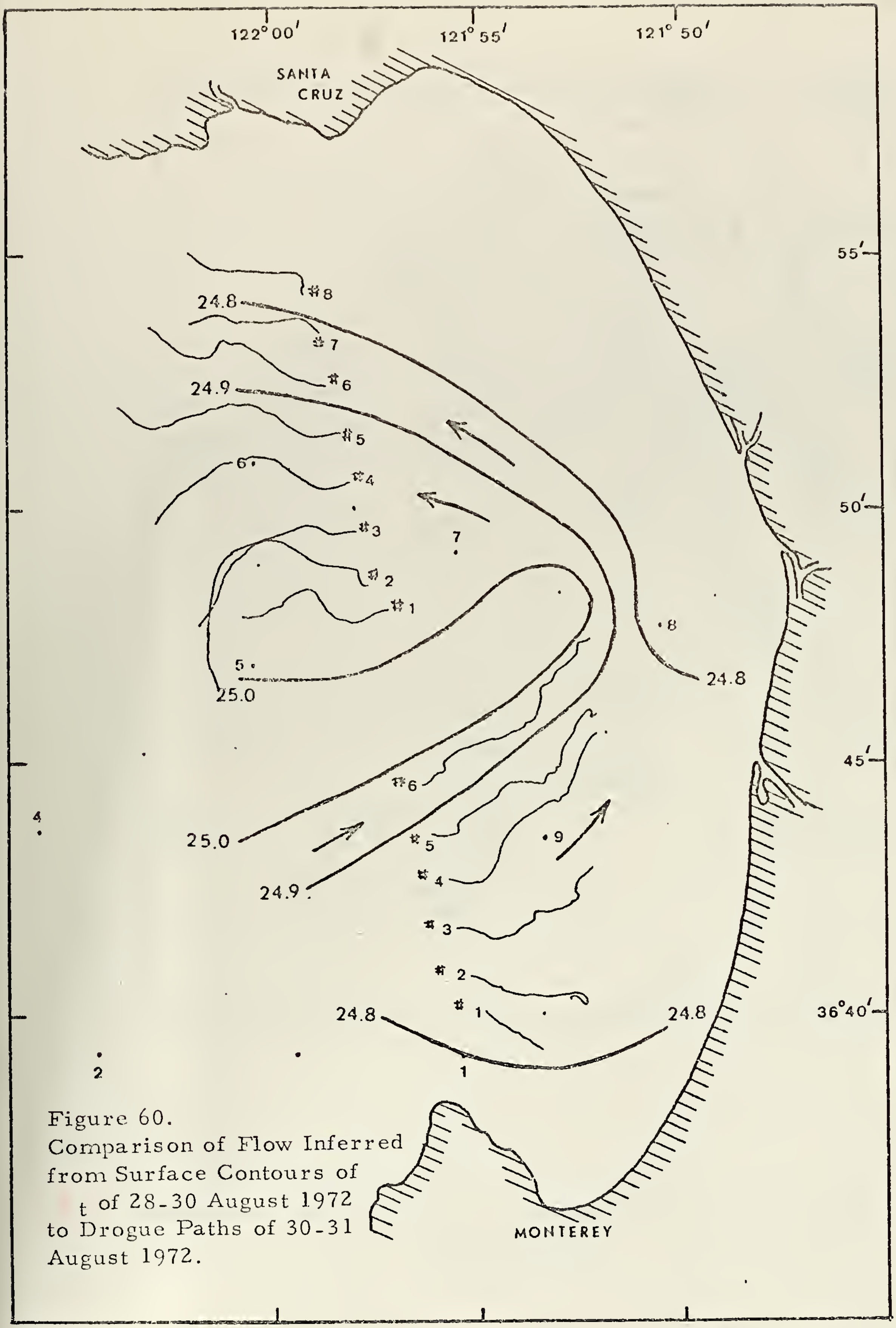


Figure 60.
Comparison of Flow Inferred from Surface Contours of $_t$ of 28-30 August 1972 to Drogue Paths of 30-31 August 1972.

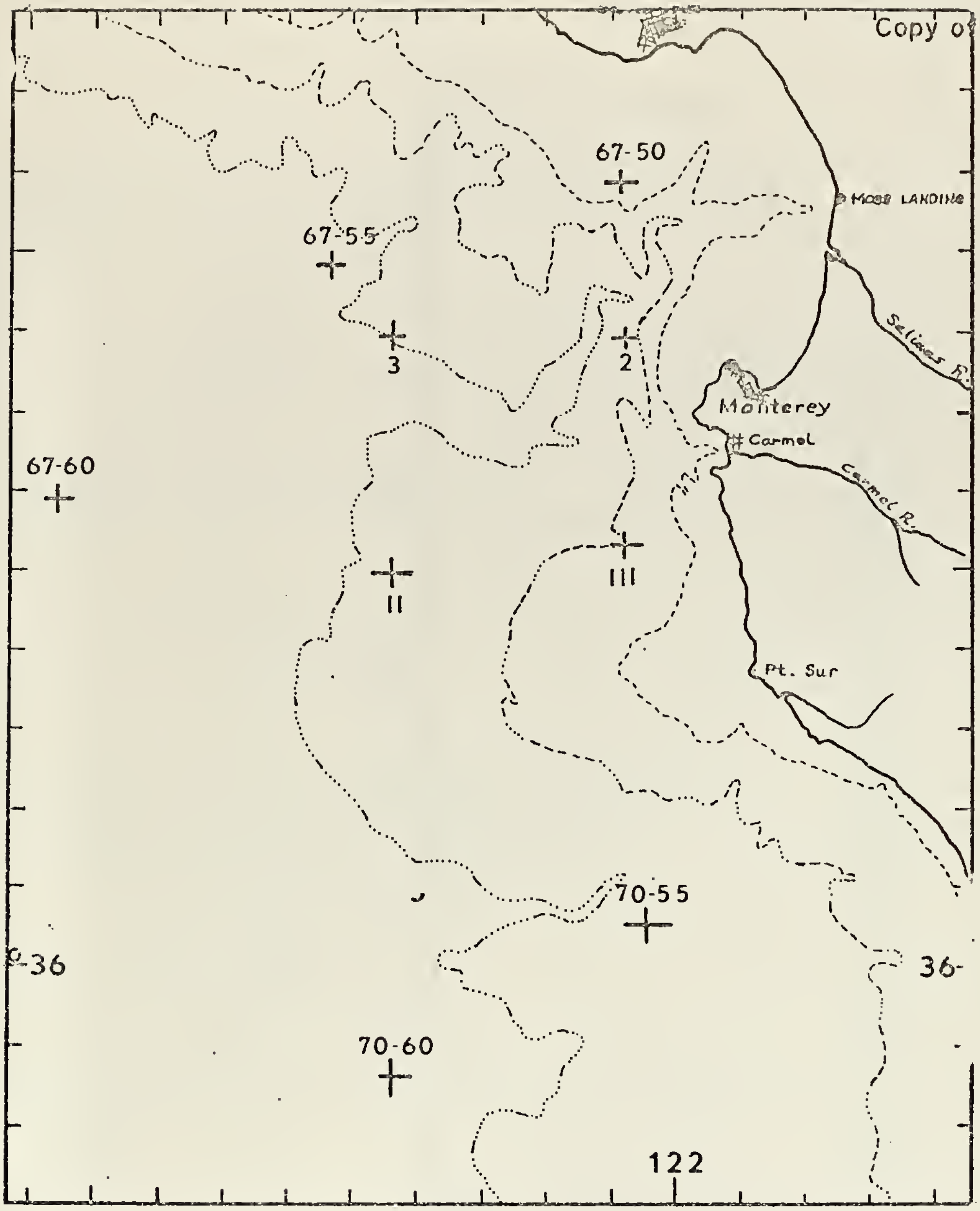


Figure 61. Stations Where Geostrophic Current Information was Available

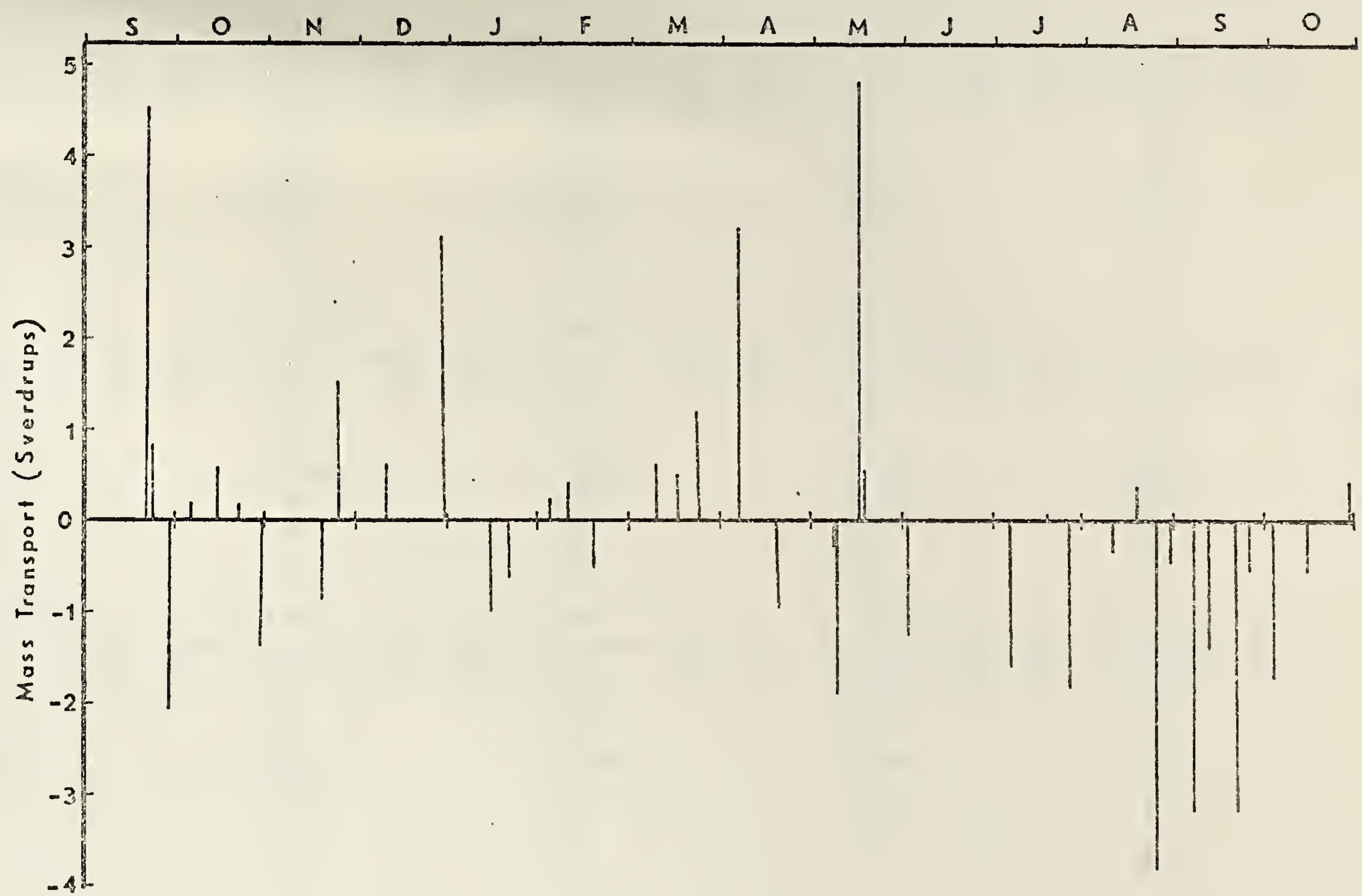


Figure 61A. Mass Transport Between Stations 2 and 3

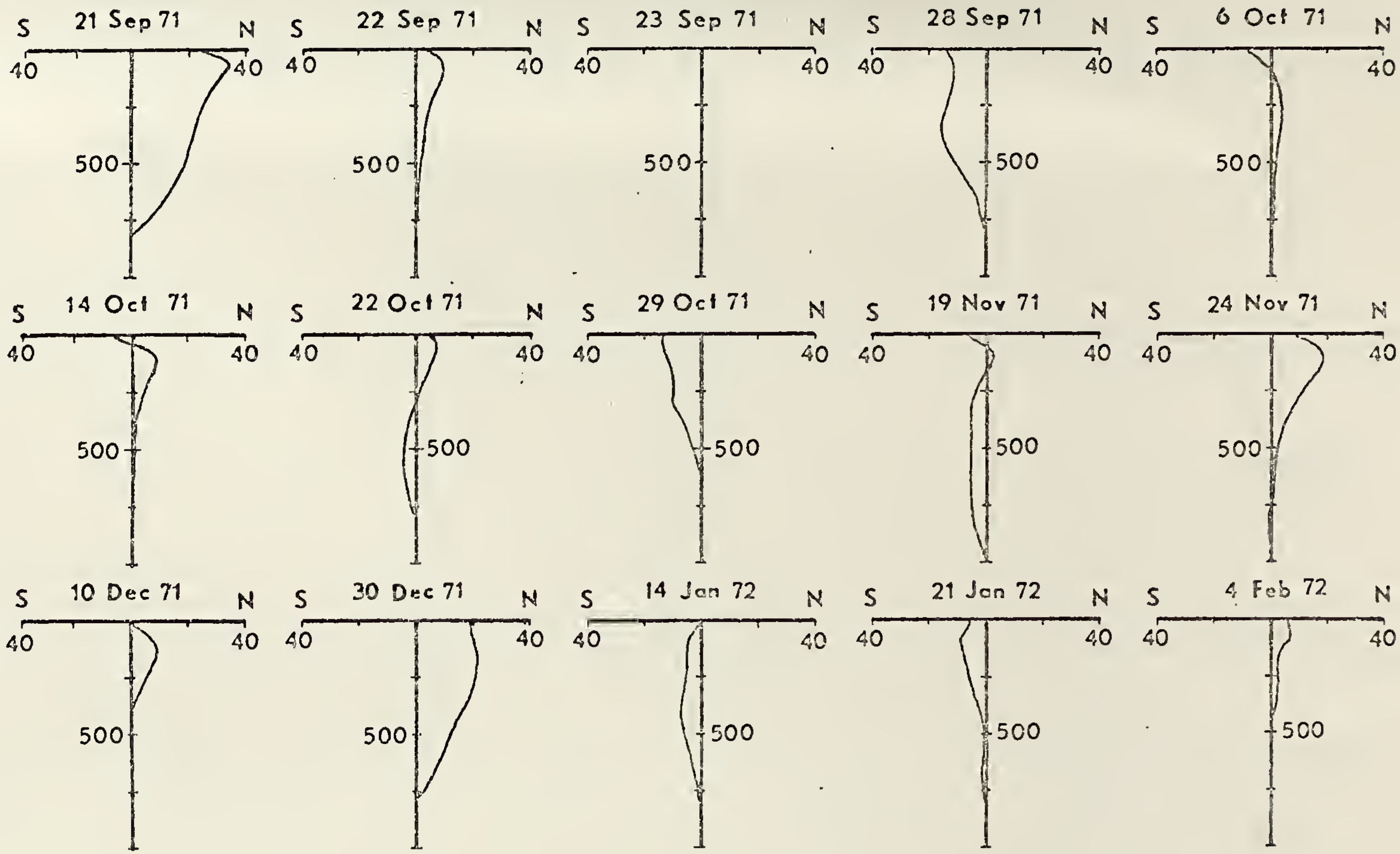


Figure 62. Geostrophic Current Profiles Between Stations 2 and 3

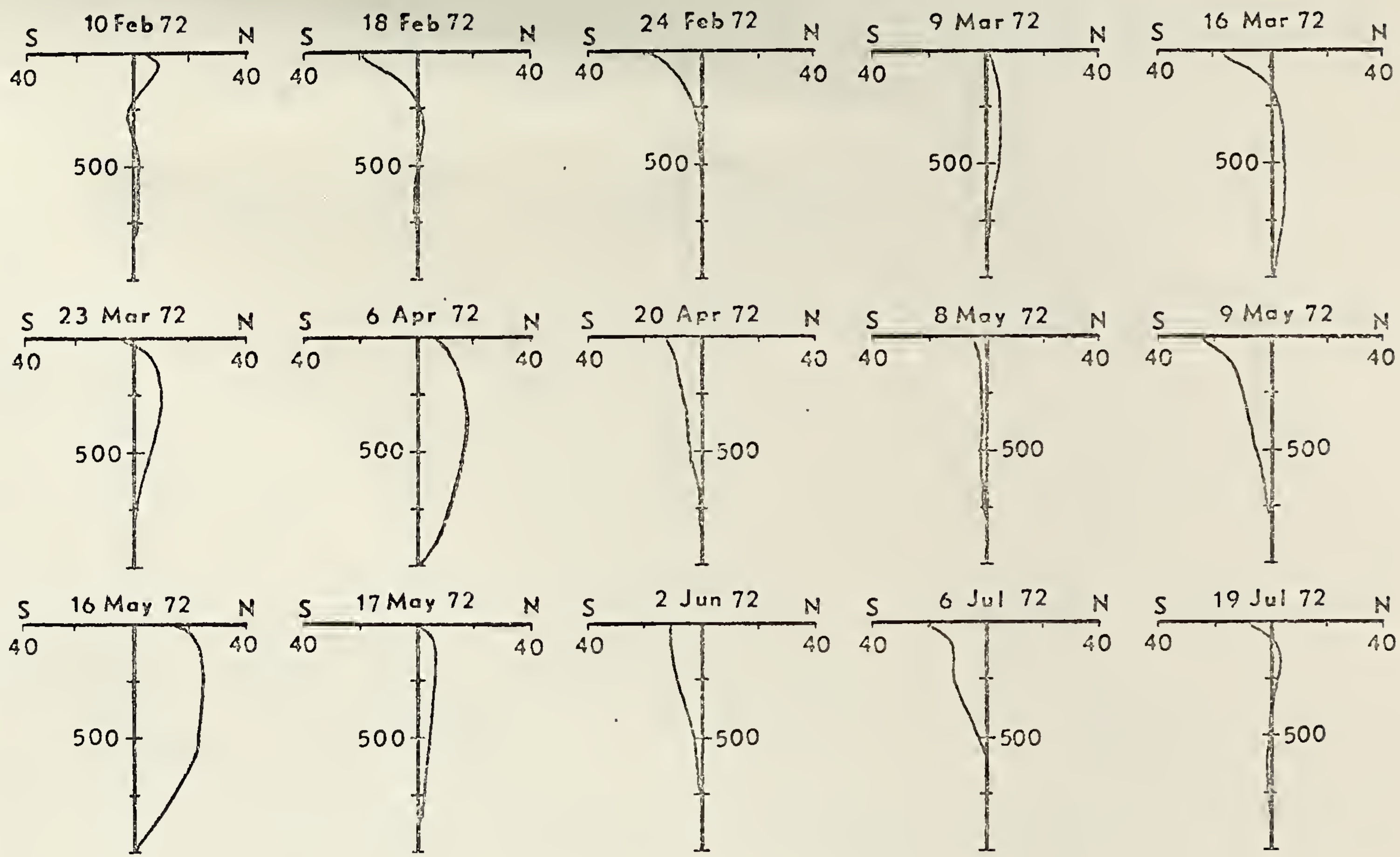


Figure 63. Geostrophic Current Profiles Between Stations 2 and 3

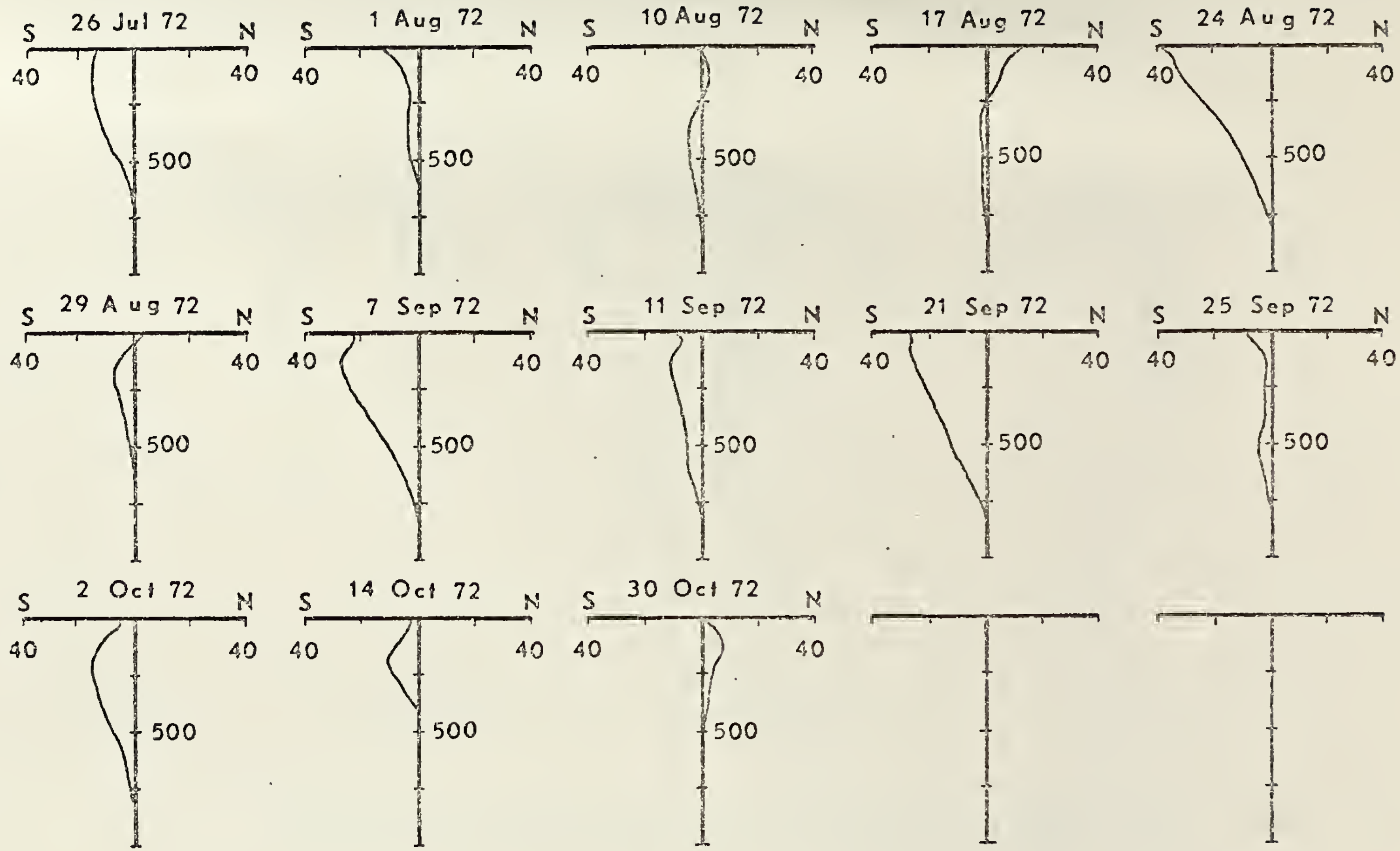


Figure 64. Geostrophic Current Profiles Between Stations 2 and 3

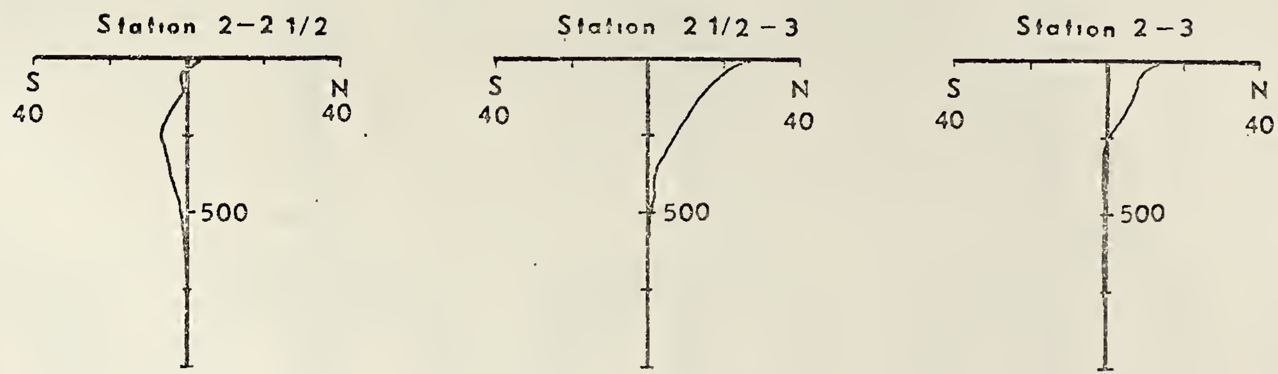


Figure 65. Geostrophic Current Profiles of 17 August 1972

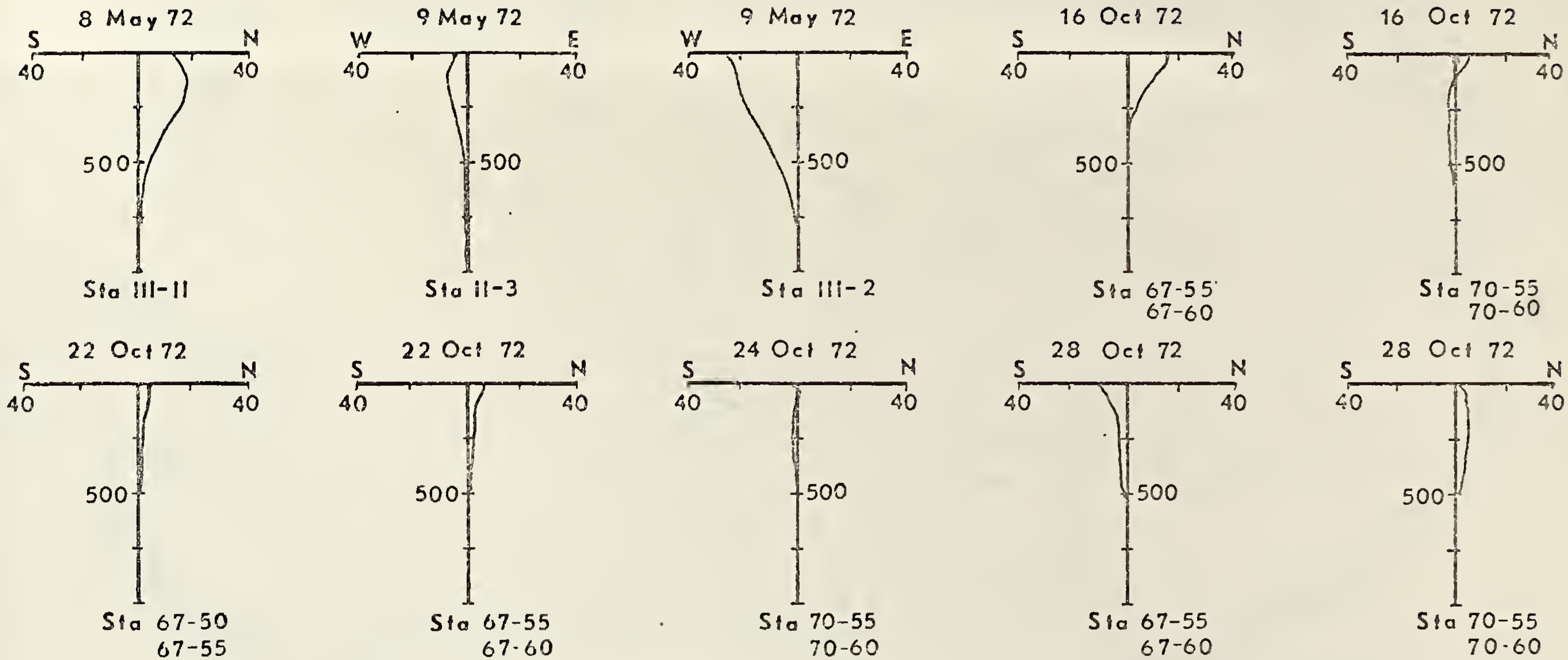


Figure 66. Geostrophic Current Profiles from Pairs of Stations near Monterey Bay

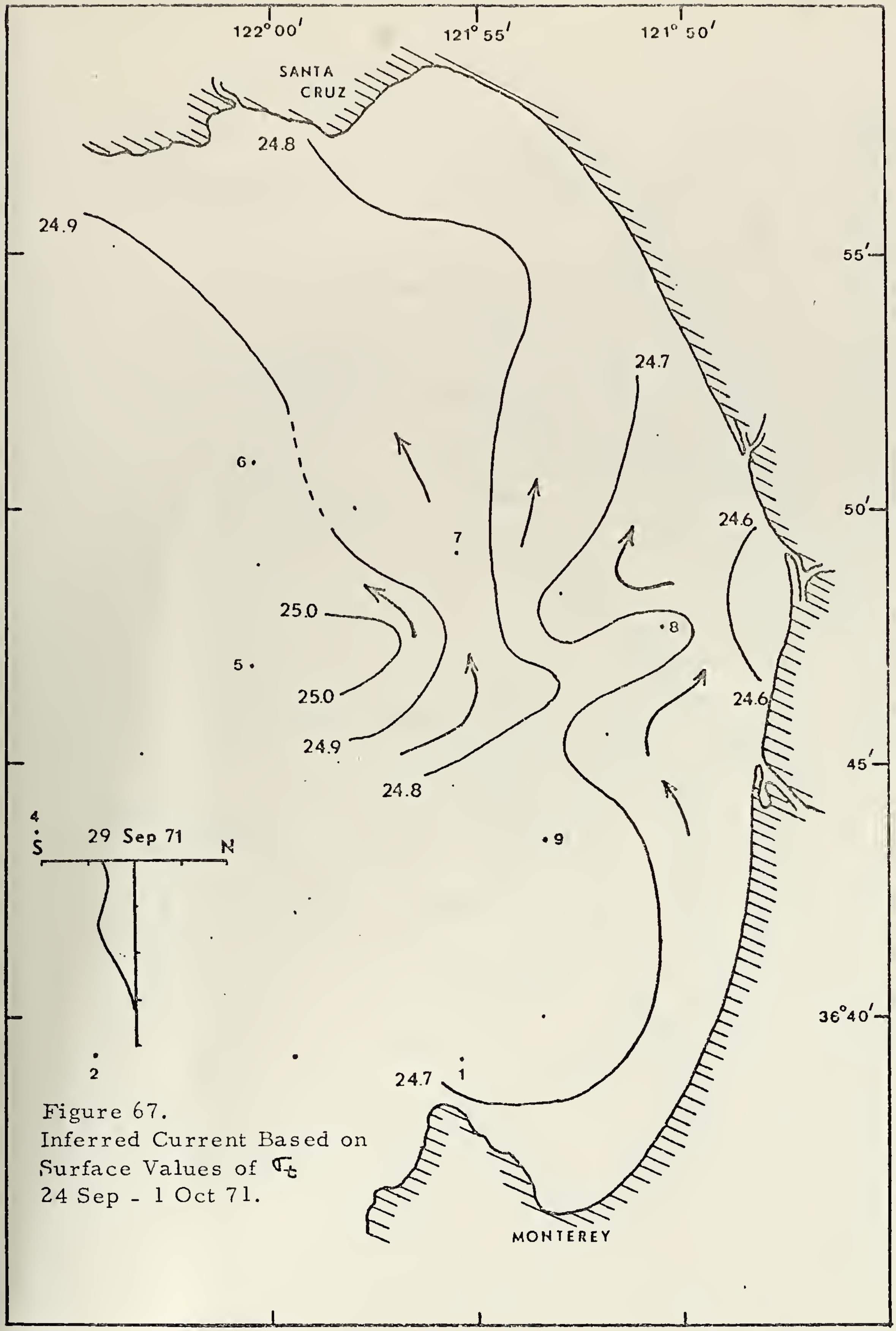


Figure 67.
Inferred Current Based on
Surface Values of σ_t
24 Sep - 1 Oct 71.

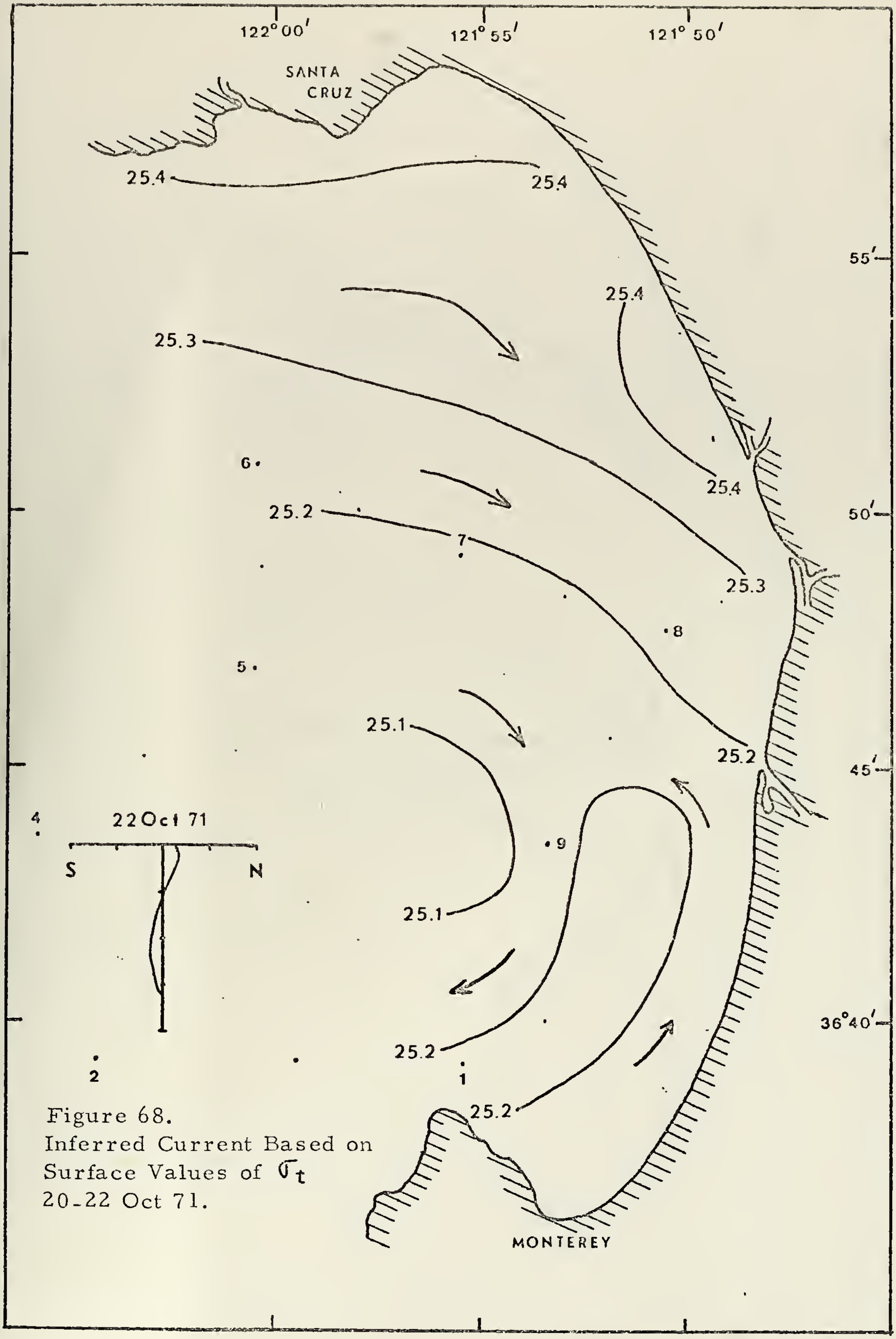


Figure 68.
Inferred Current Based on Surface Values of σ_t
20-22 Oct 71.

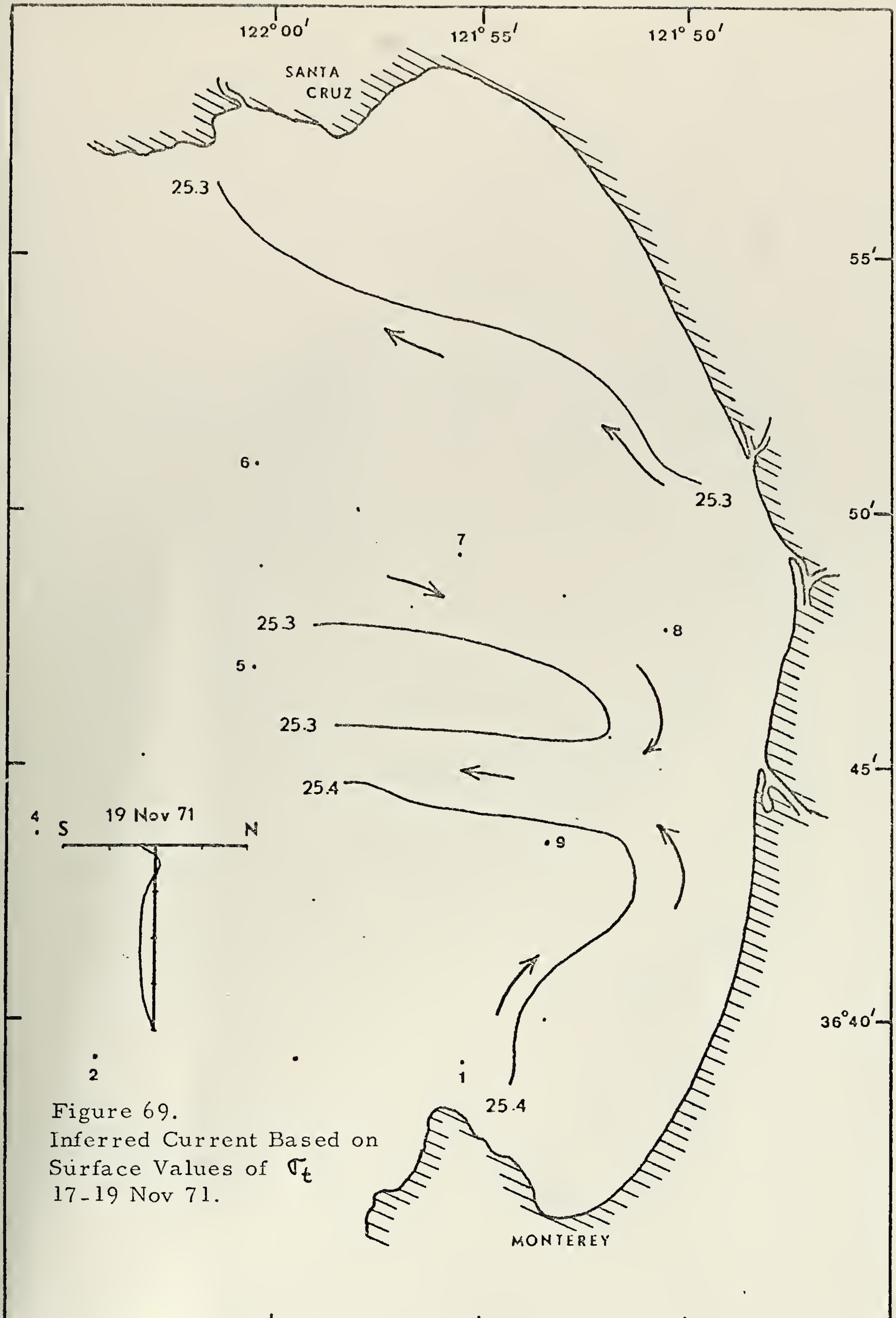


Figure 69.
Inferred Current Based on
Surface Values of σ_t
17-19 Nov 71.

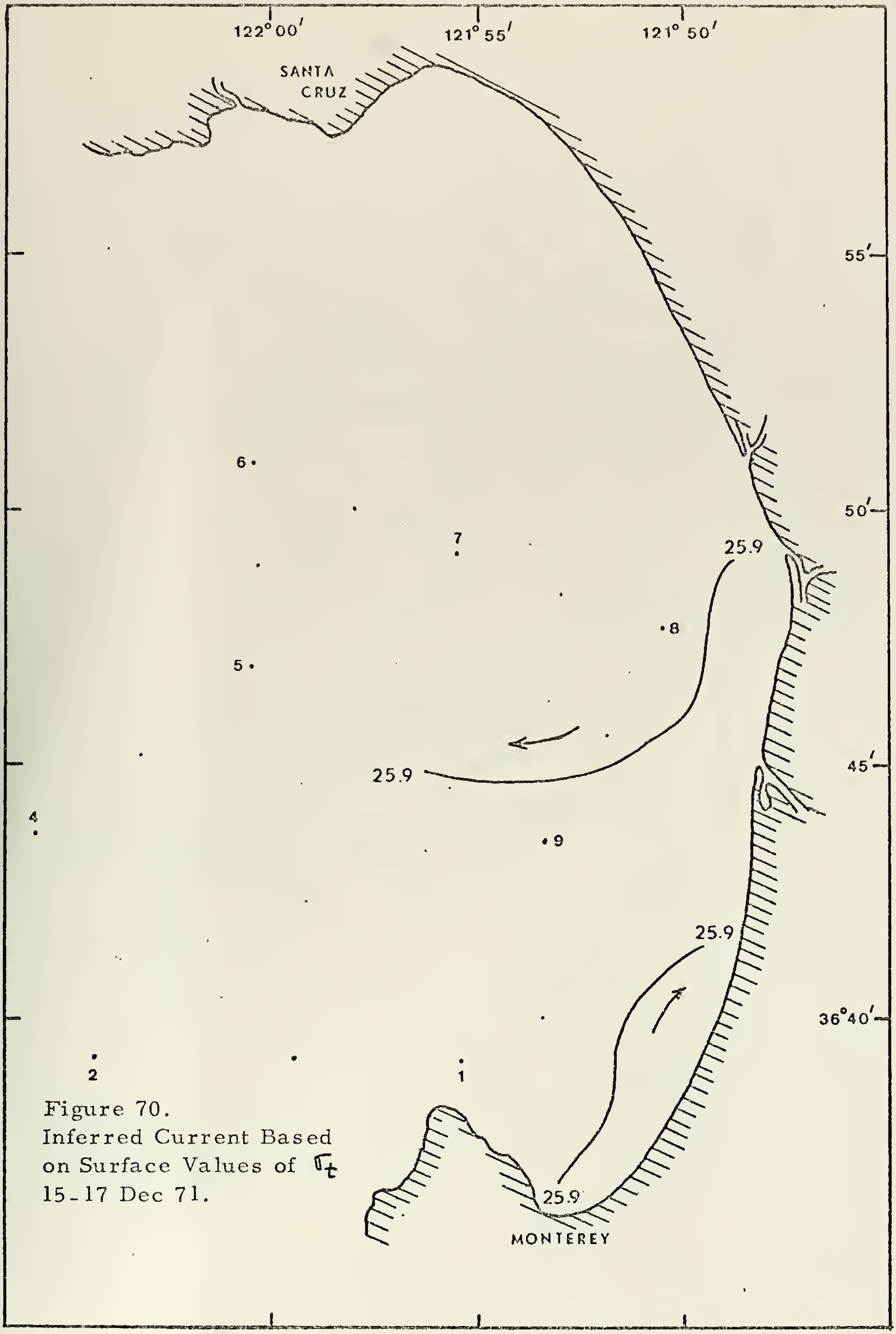


Figure 70.
Inferred Current Based on Surface Values of σ_t 15-17 Dec 71.

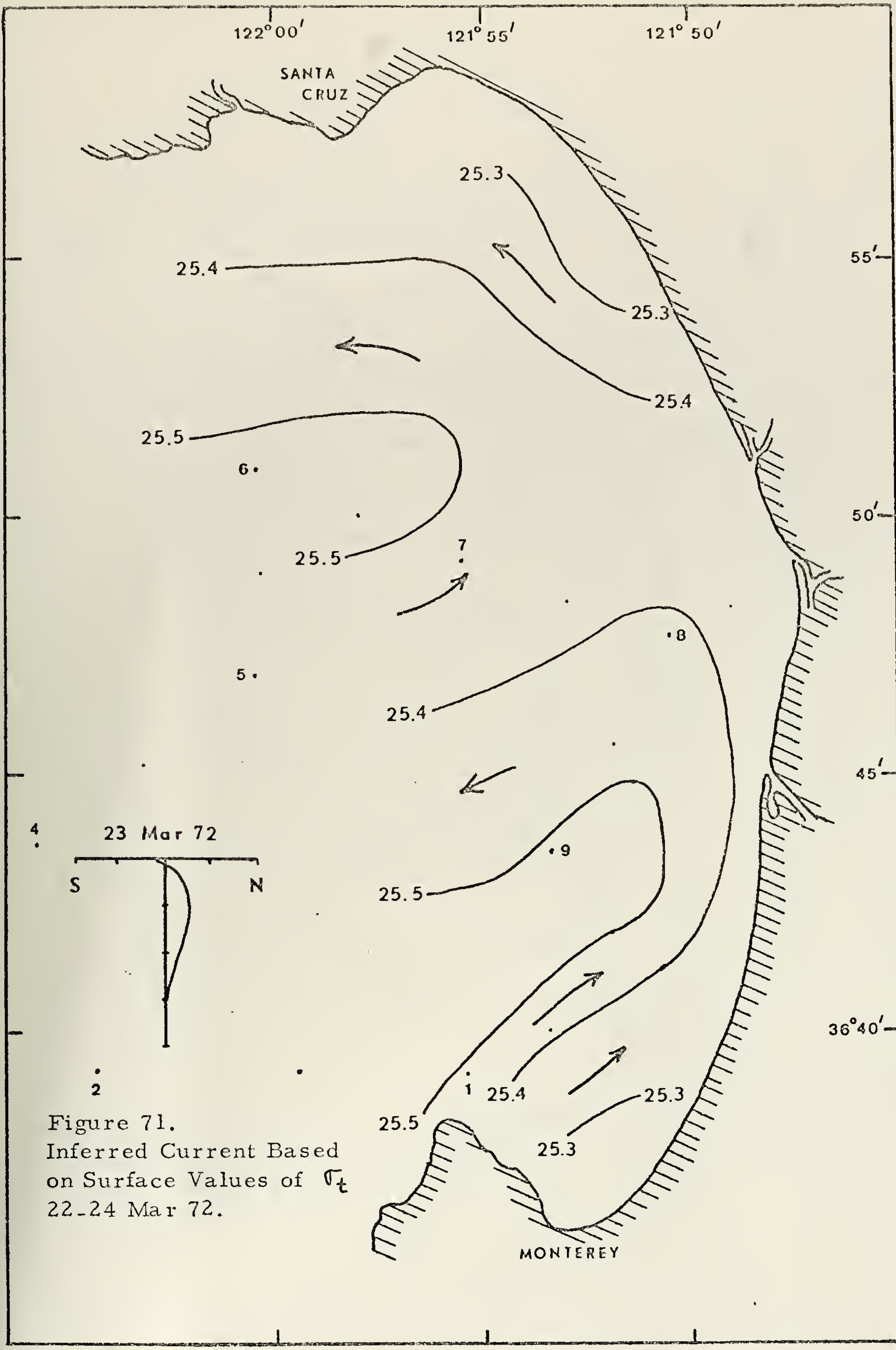


Figure 71.
Inferred Current Based on Surface Values of σ_t 22-24 Mar 72.

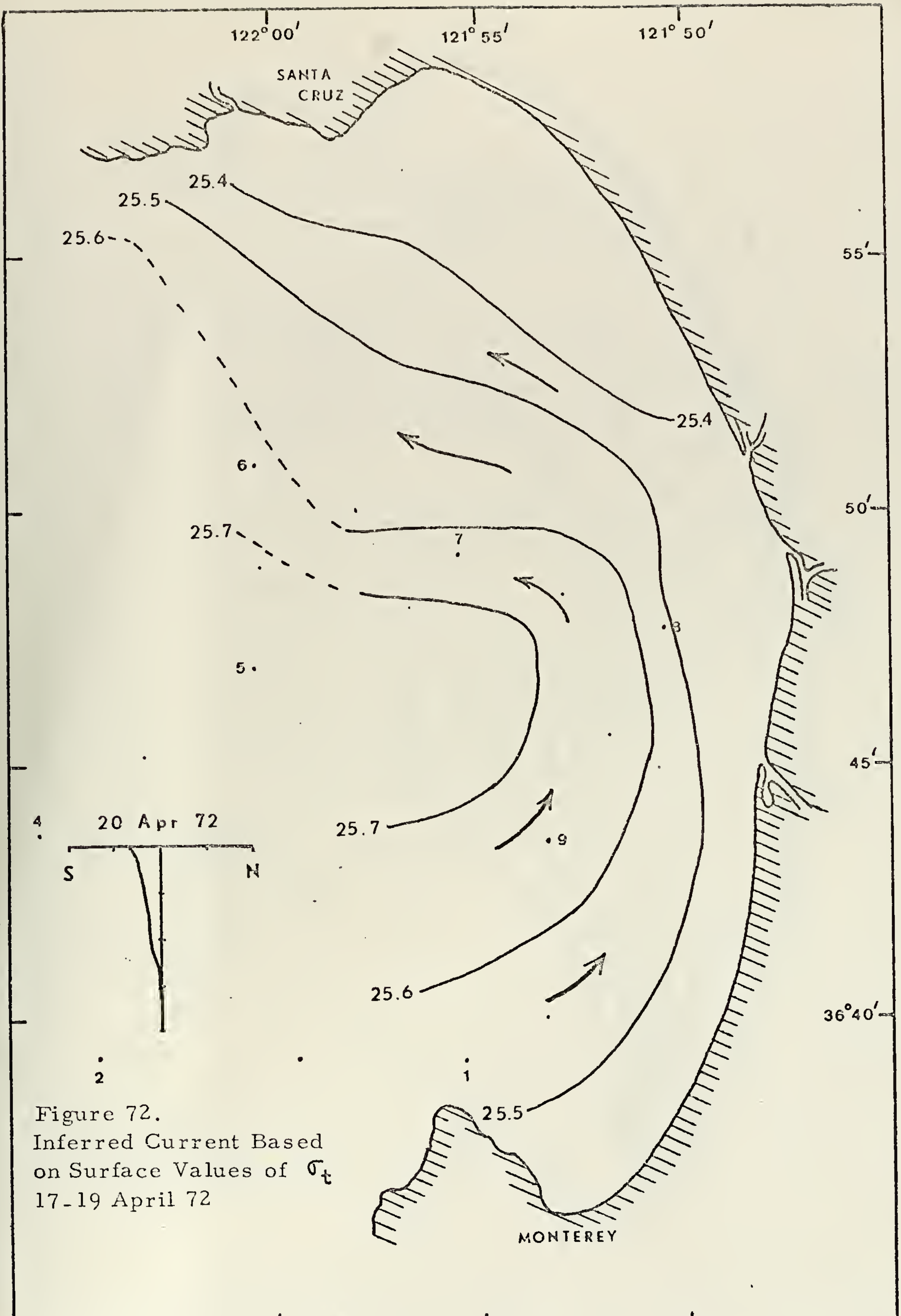


Figure 72.
Inferred Current Based on Surface Values of σ_t 17-19 April 72

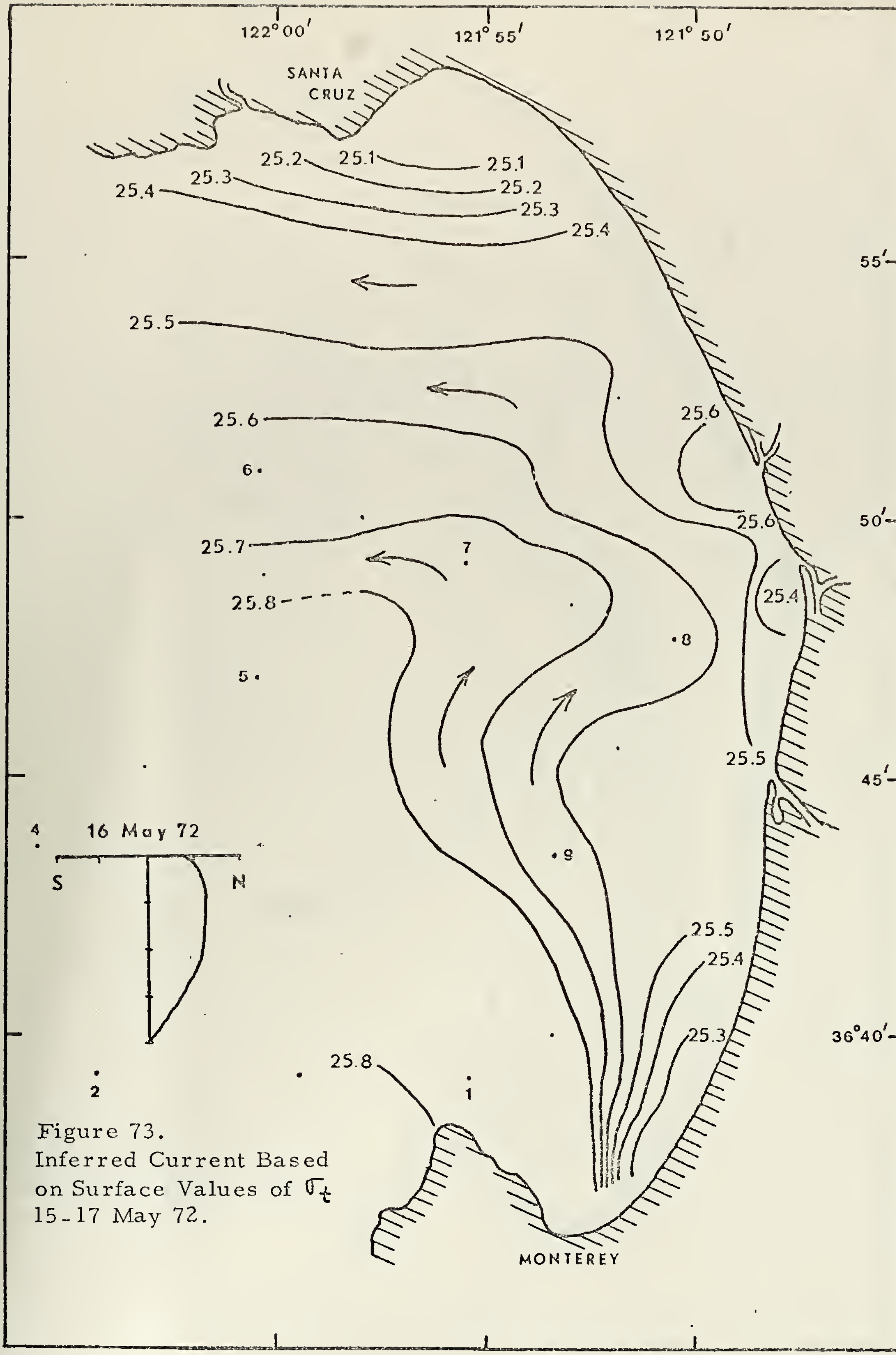


Figure 73.
Inferred Current Based on Surface Values of σ_t 15-17 May 72.

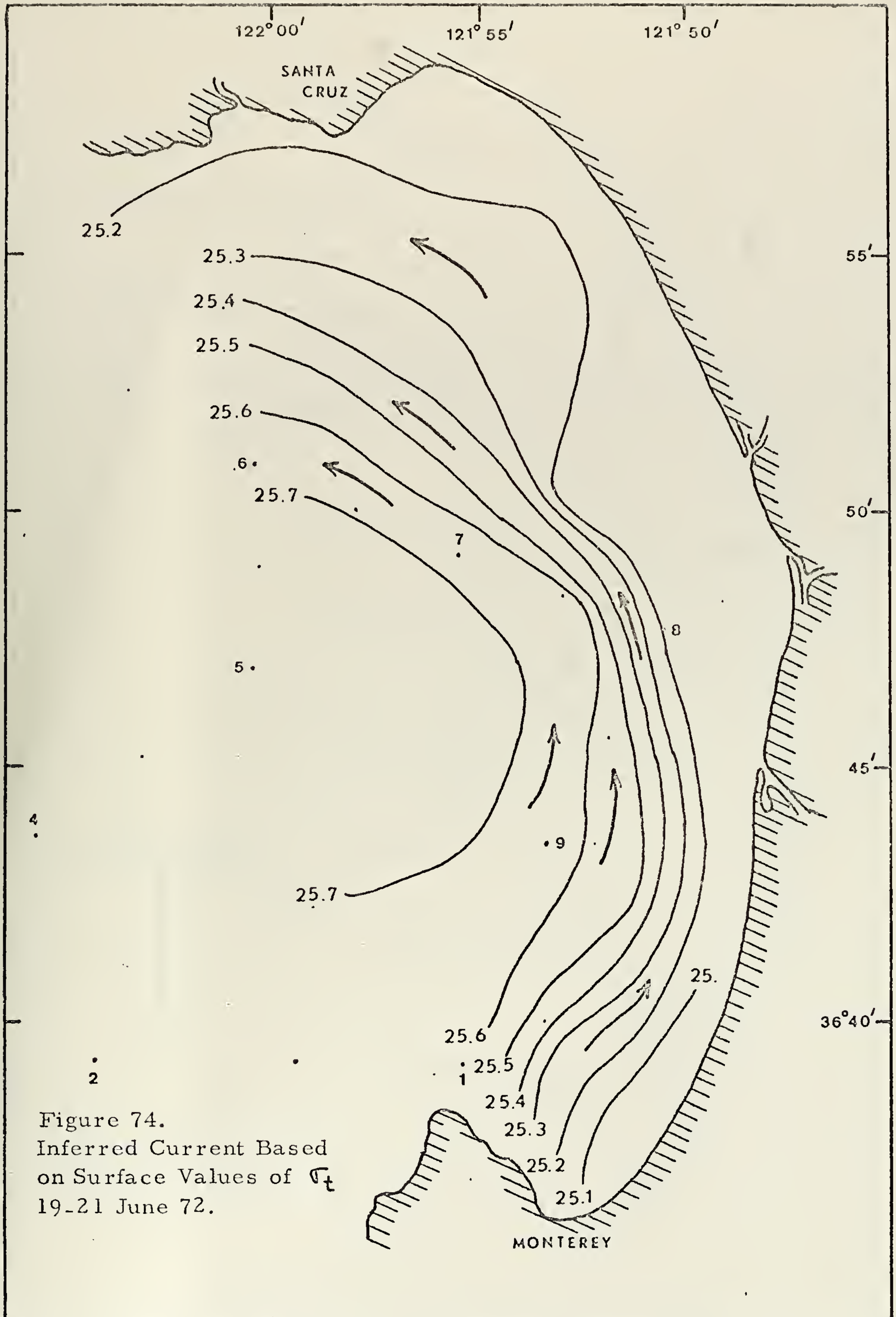


Figure 74.
Inferred Current Based on Surface Values of σ_t 19-21 June 72.

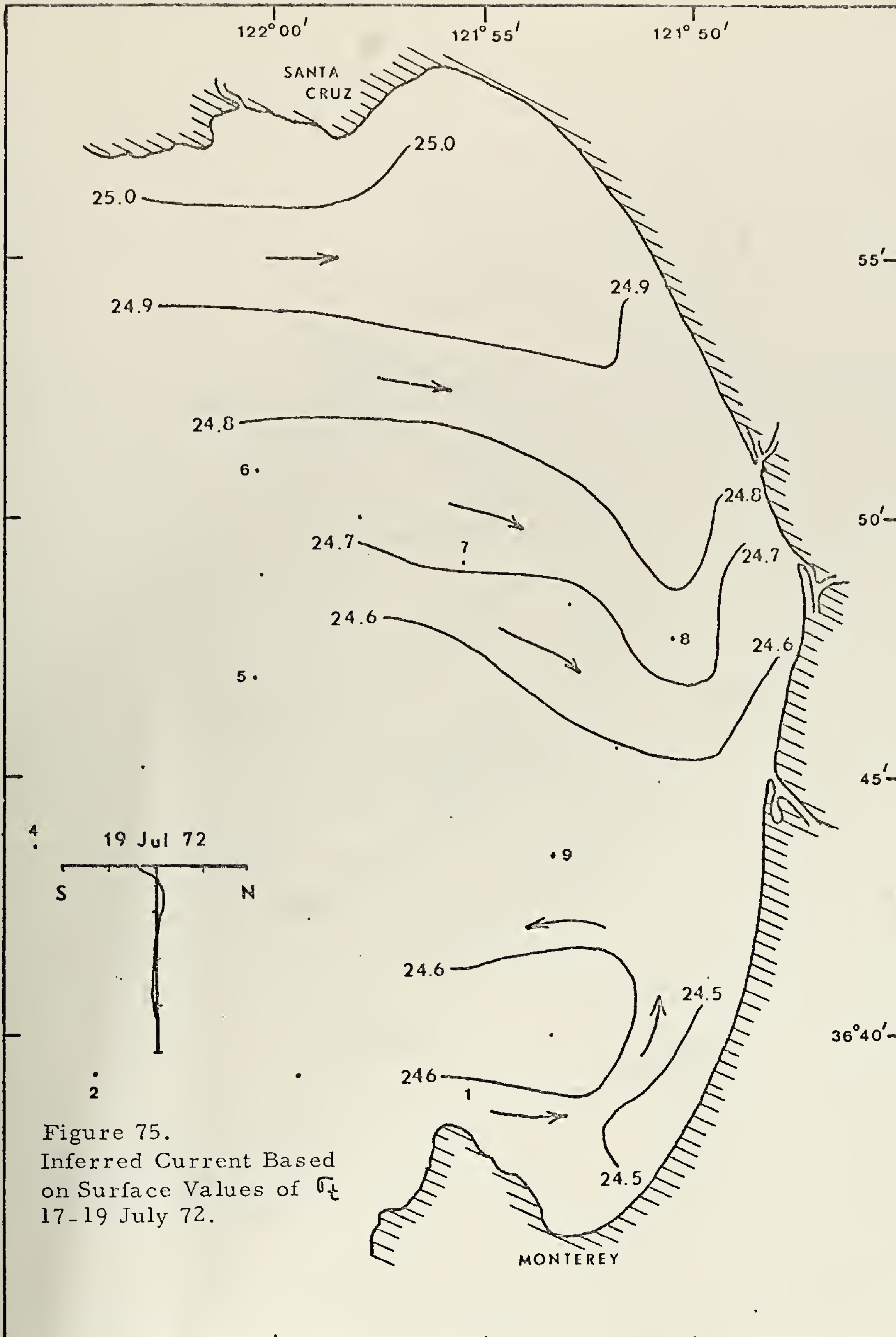


Figure 75.
Inferred Current Based on Surface Values of σ_t 17-19 July 72.

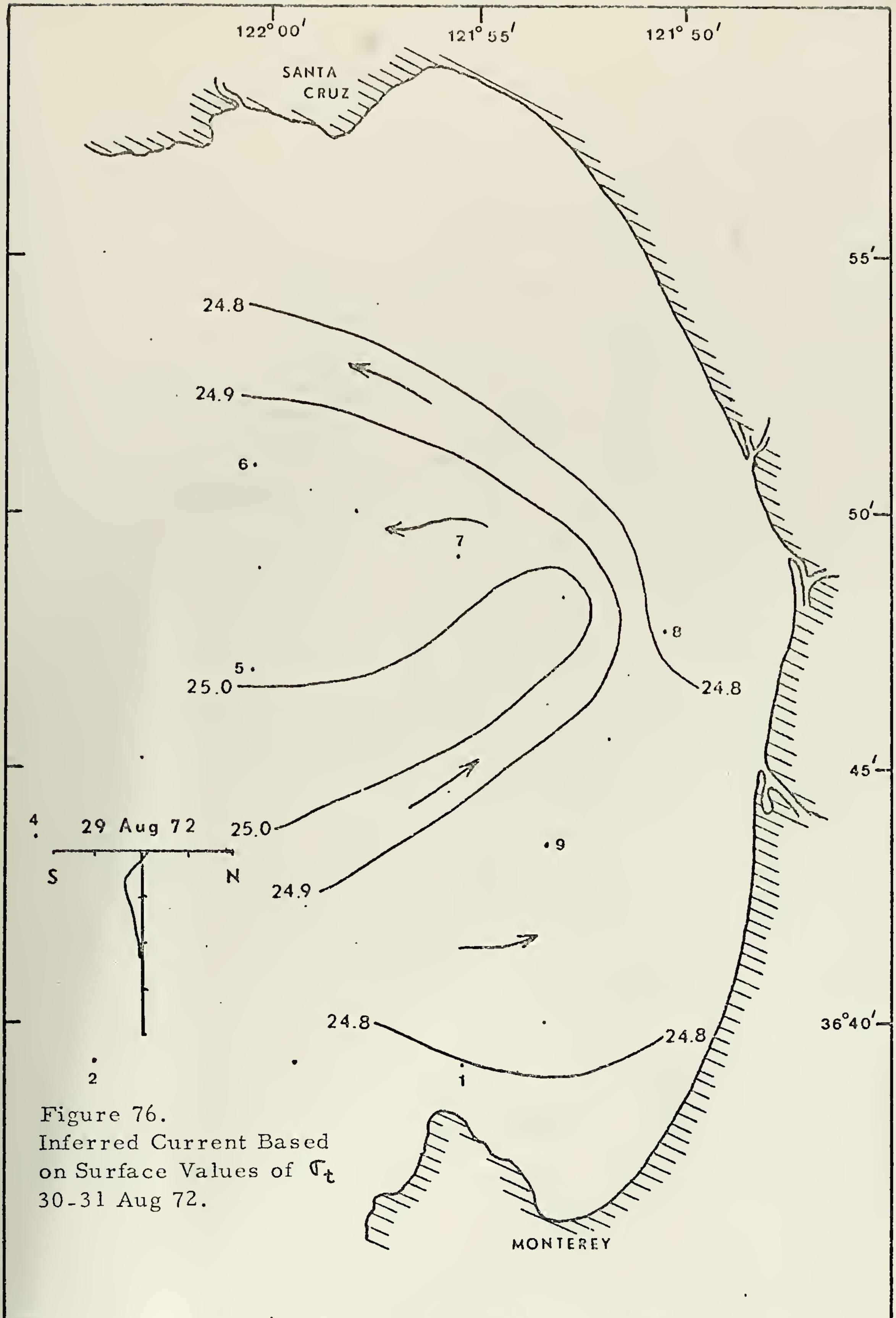


Figure 76.
Inferred Current Based on Surface Values of σ_t 30-31 Aug 72.

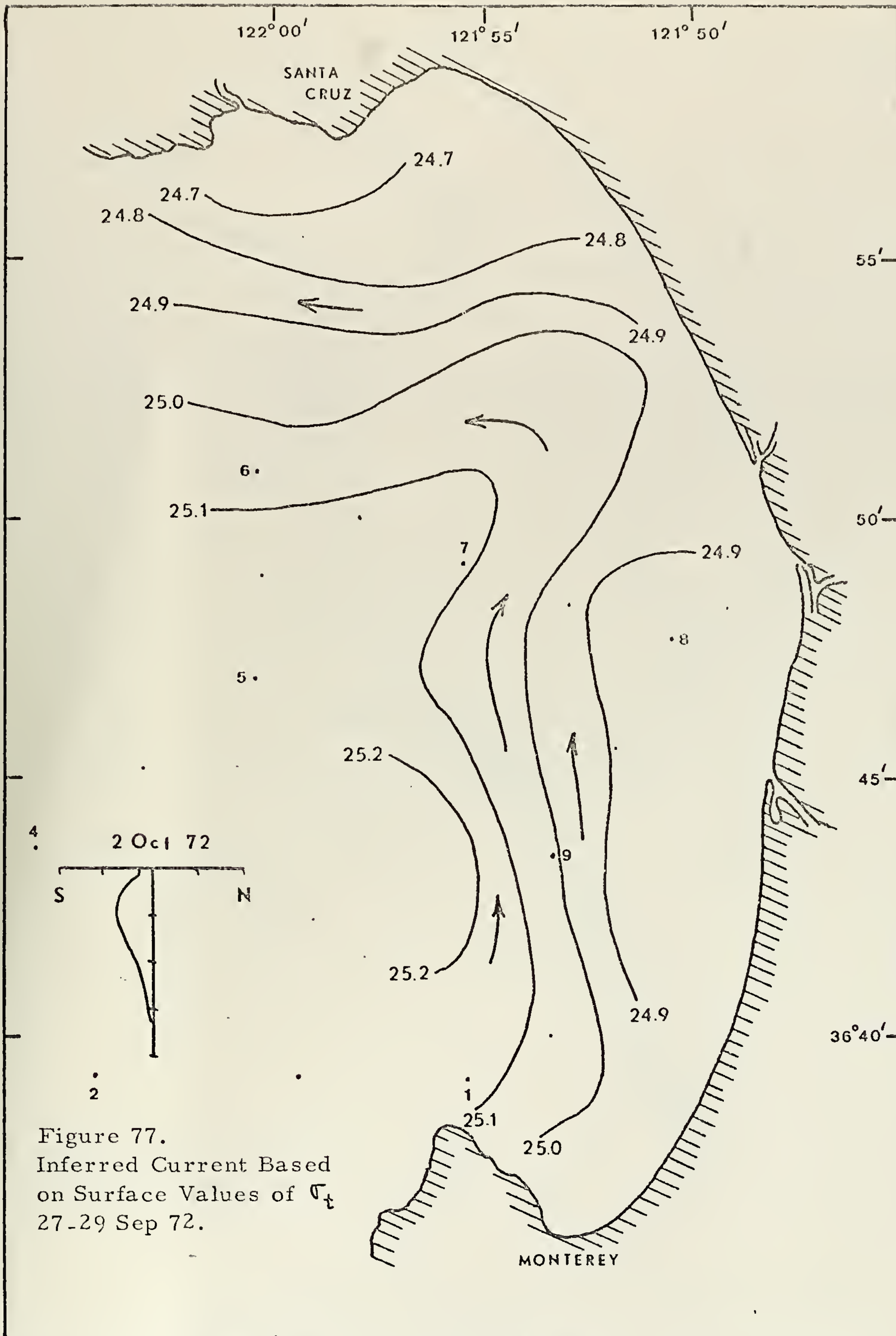


Figure 77.
Inferred Current Based on Surface Values of σ_t 27-29 Sep 72.

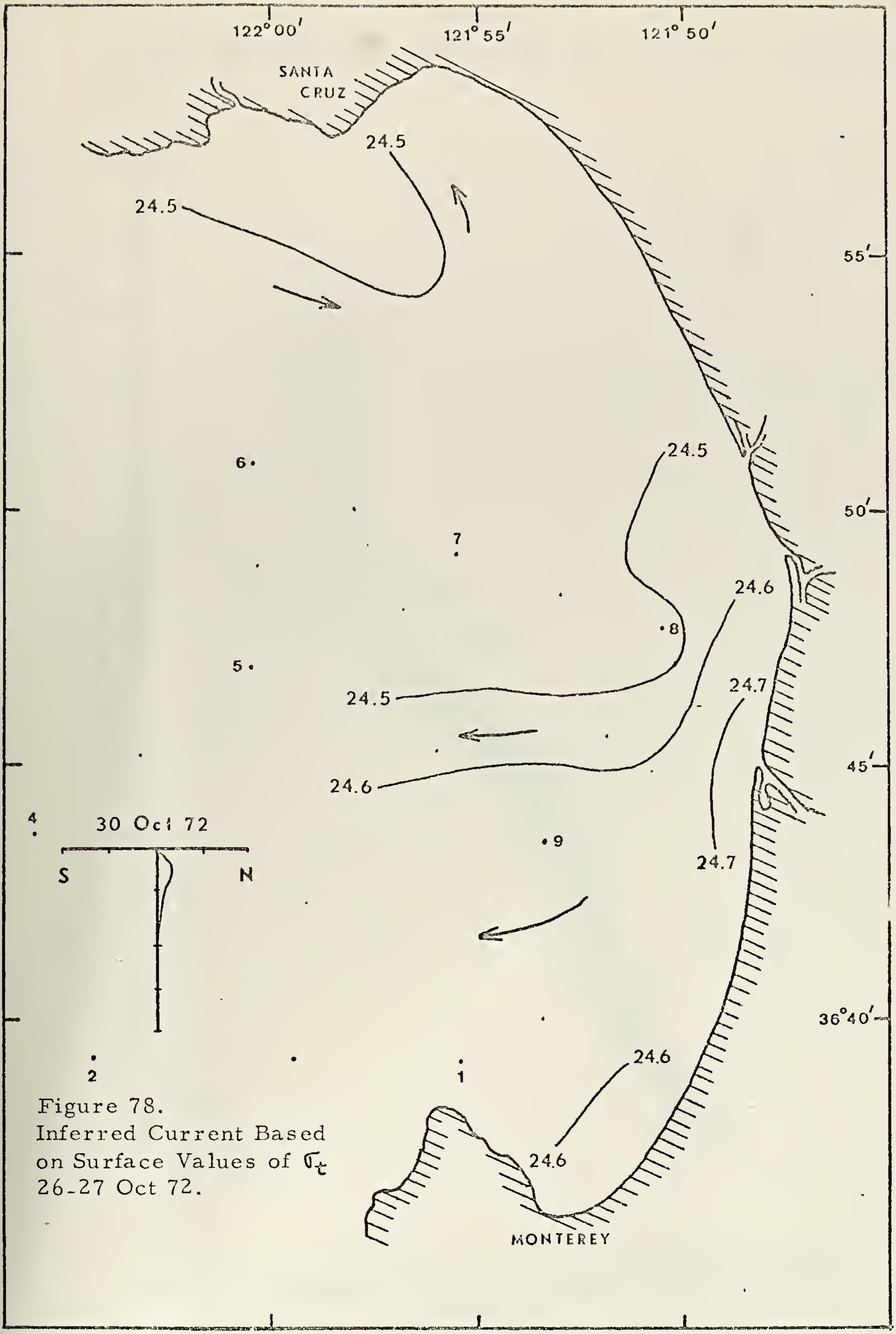


Figure 78.
Inferred Current Based on Surface Values of σ_t 26-27 Oct 72.

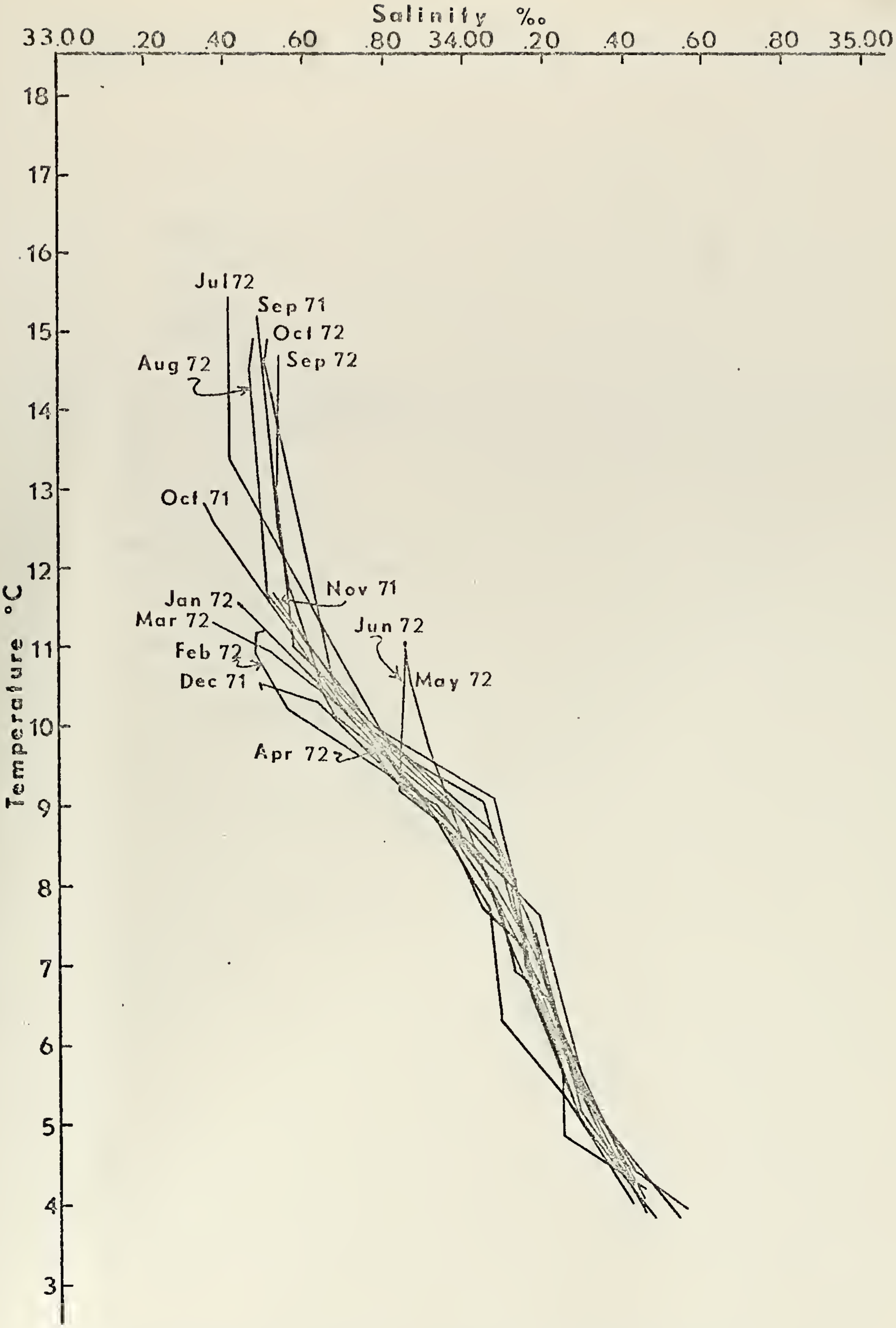


Figure 79. Typical Monthly Temperature-Salinity Curves at Station 2

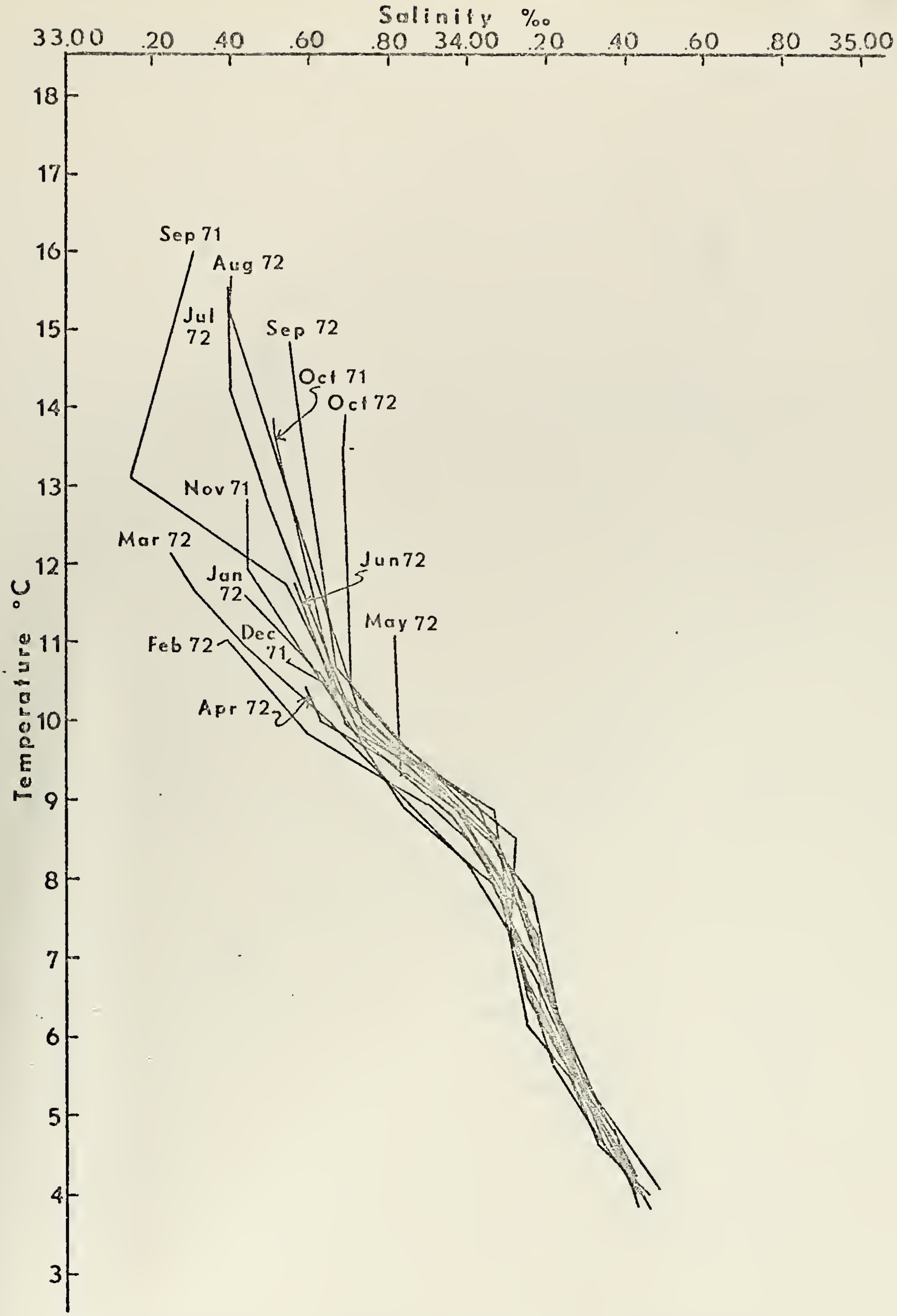


Figure 80. Typical Monthly Temperature-Salinity Curves at Station 3

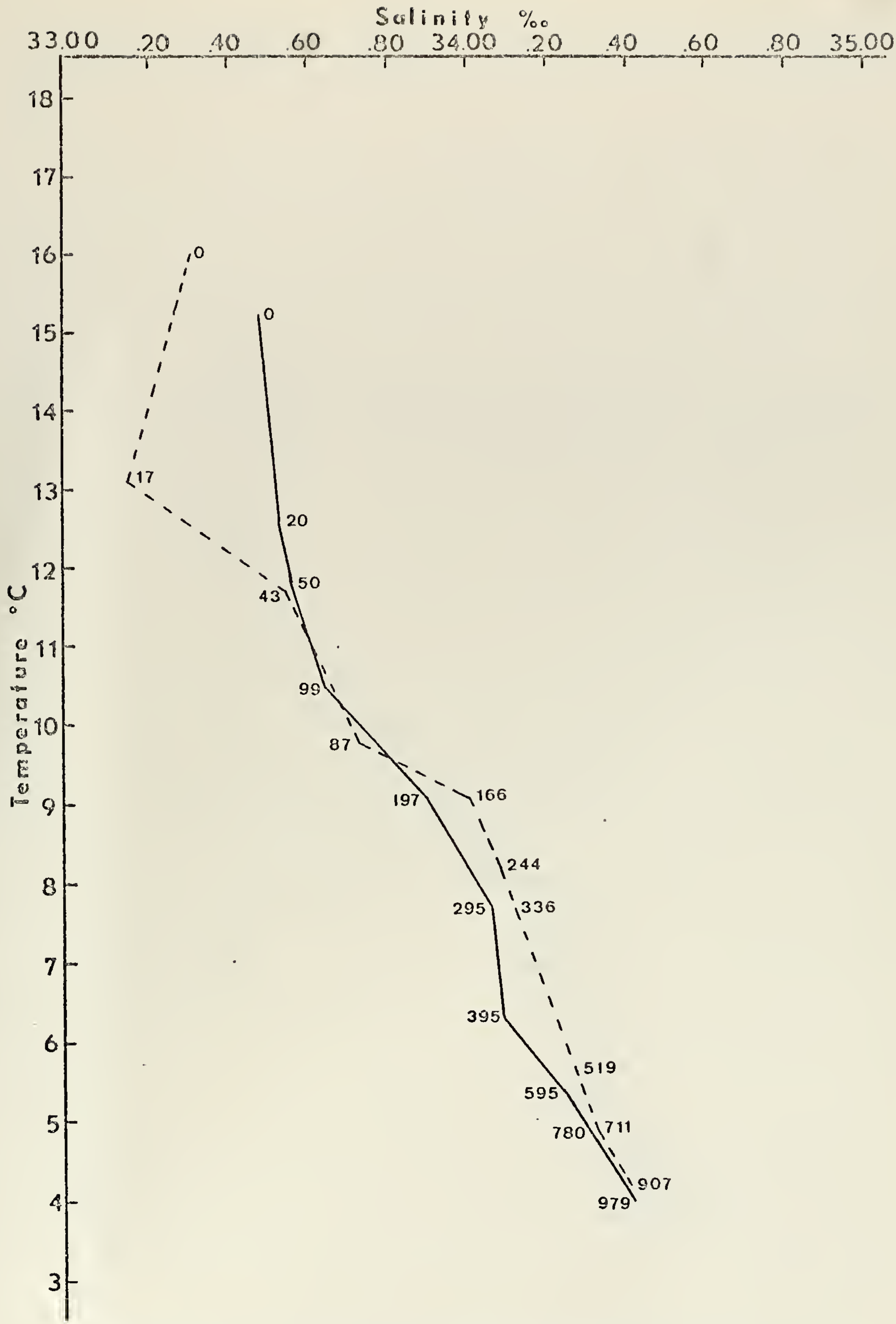


Figure 81. Typical Temperature-Salinity Curves for Stations 2 and 3 for September 1971

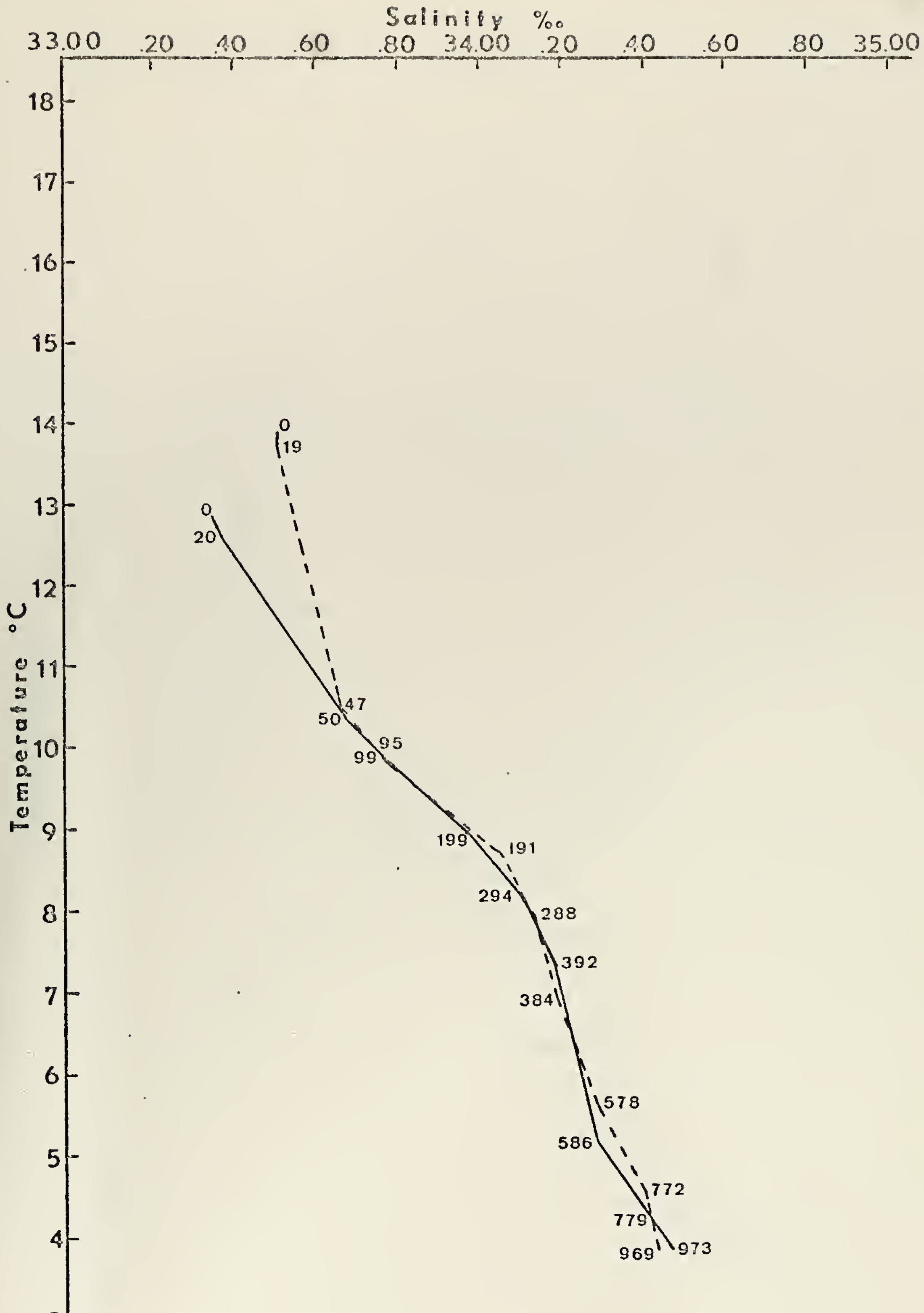


Figure 82. Typical Temperature-Salinity Curves for Stations 2 and 3 for October 1971

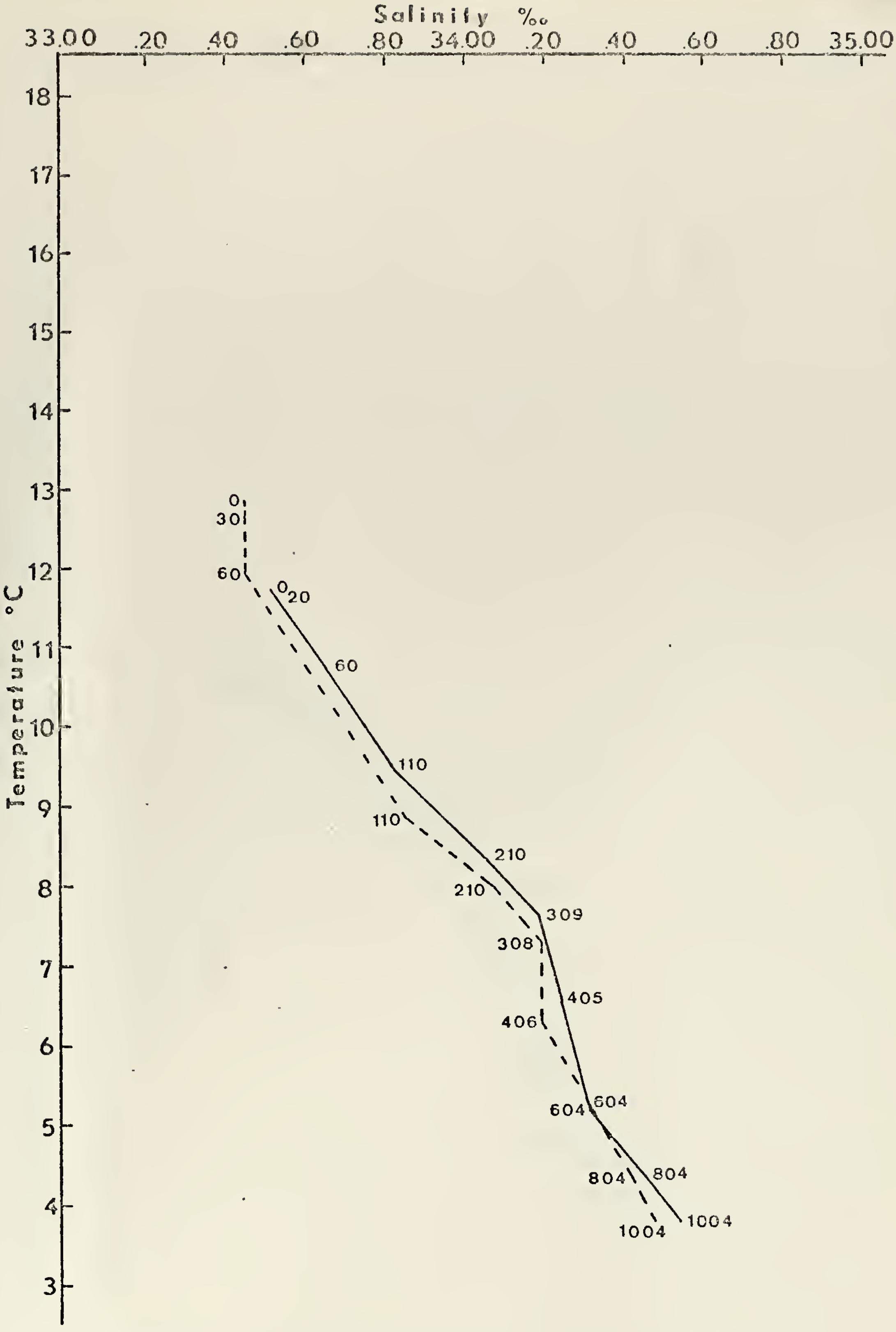


Figure 83. Typical Temperature-Salinity Curves for Stations 2 and 3 for November 1971

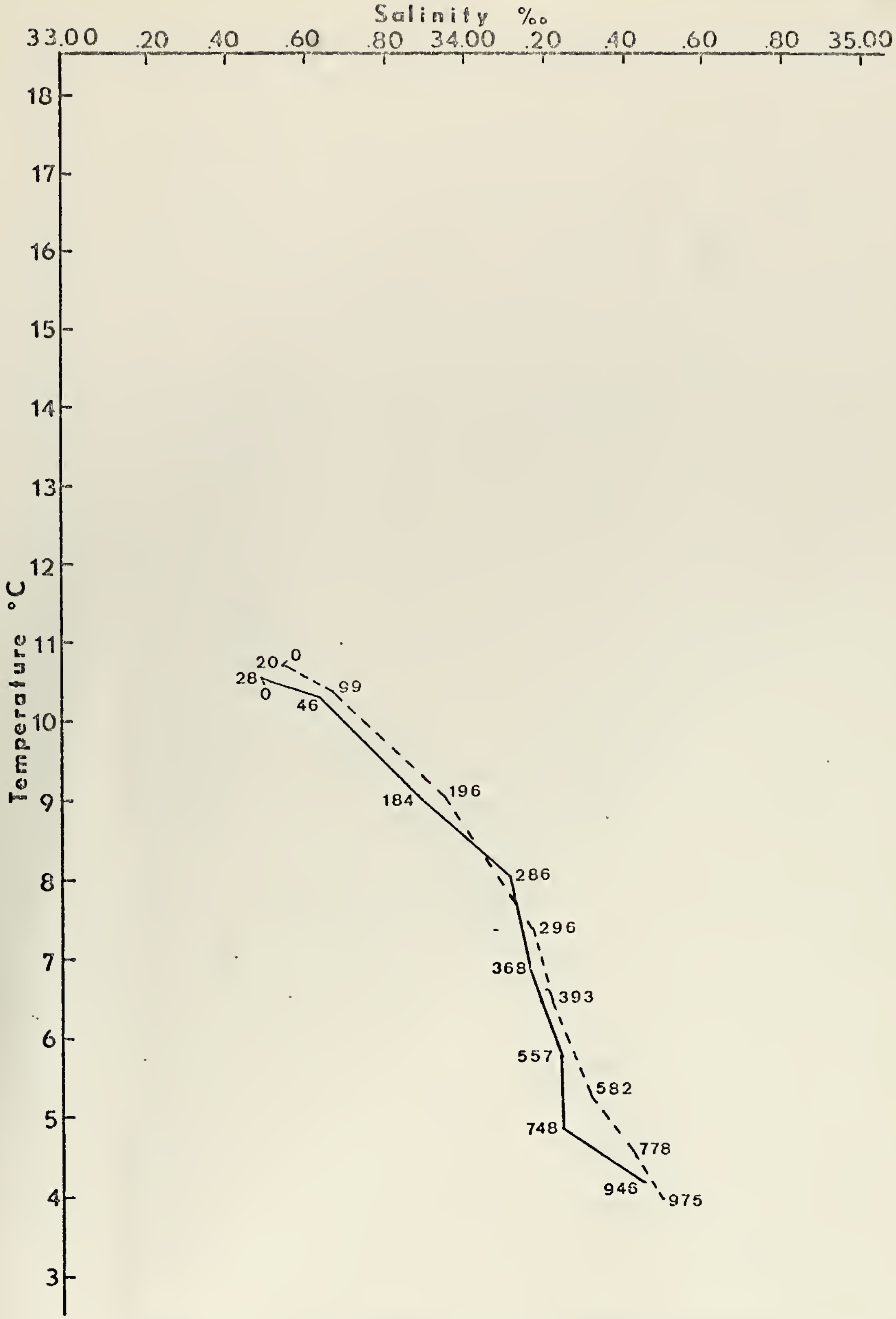


Figure 84. Typical Temperature-Salinity Curves for Stations 2 and 3 for December 1971

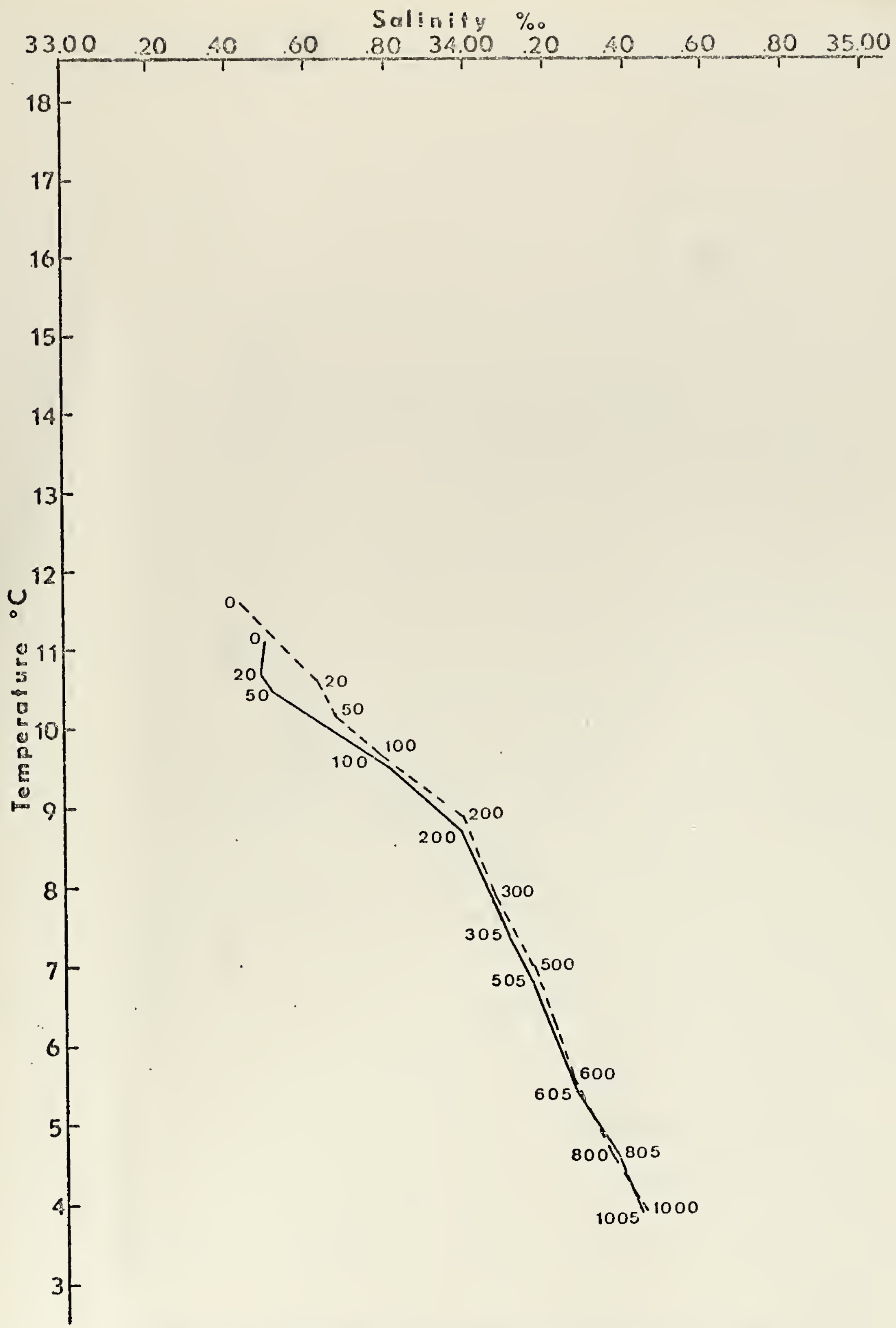


Figure 85. Typical Temperature-Salinity Curves for Stations 2 and 3 for January 1972

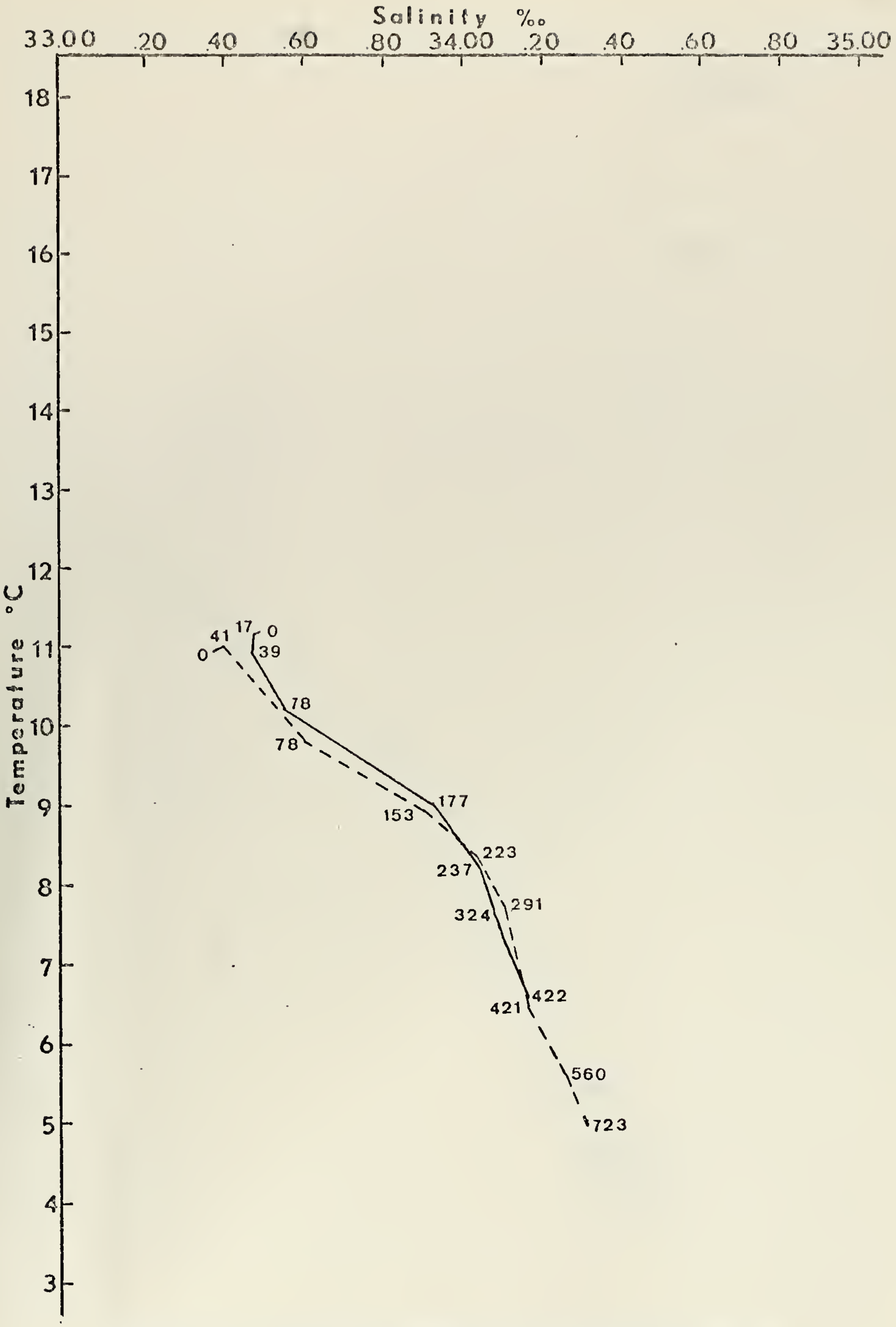


Figure 86. Typical Temperature-Salinity Curves
for Stations 2 and 3 for February 1972

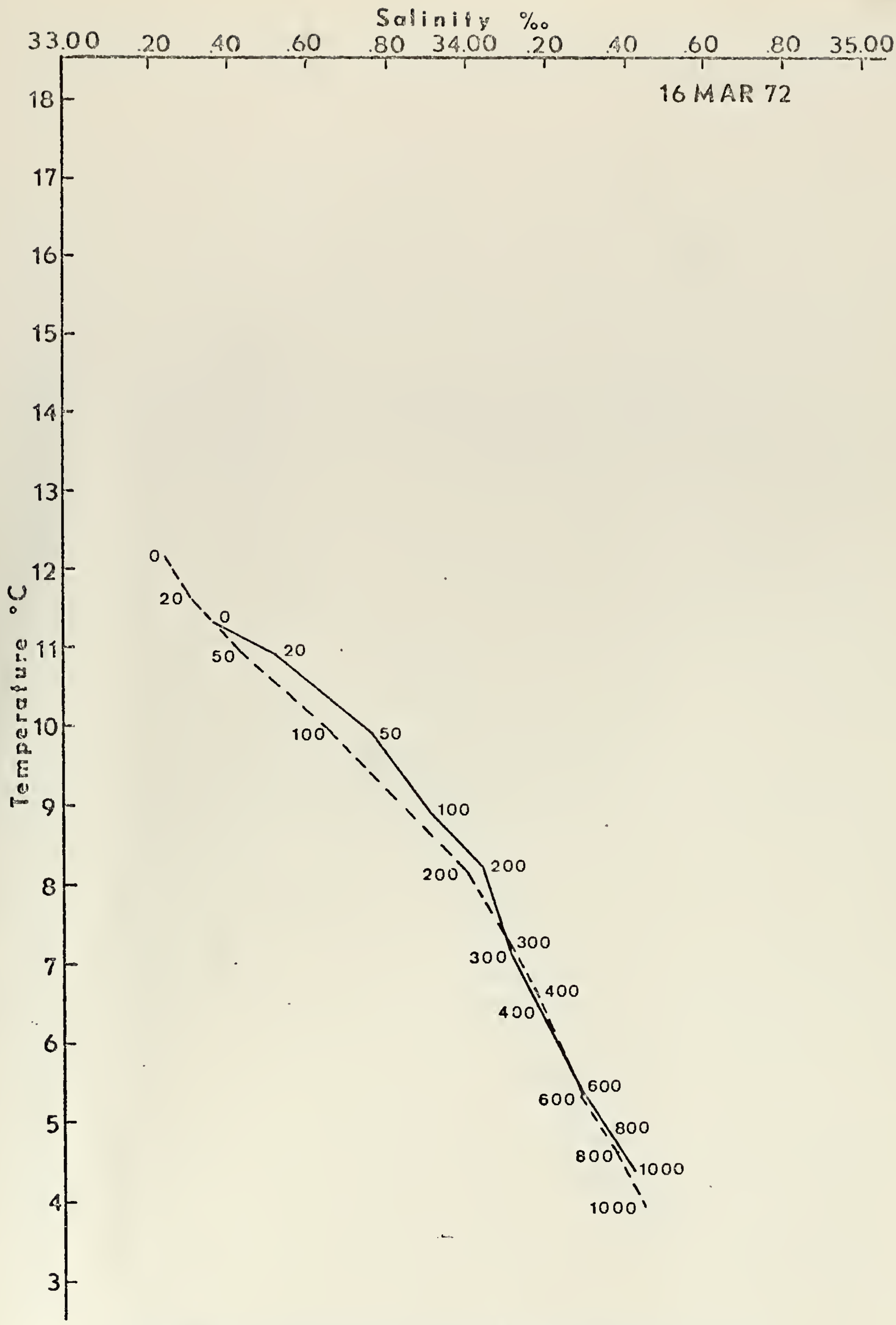


Figure 87. Typical Temperature-Salinity Curves for Stations 2 and 3 for March 1972

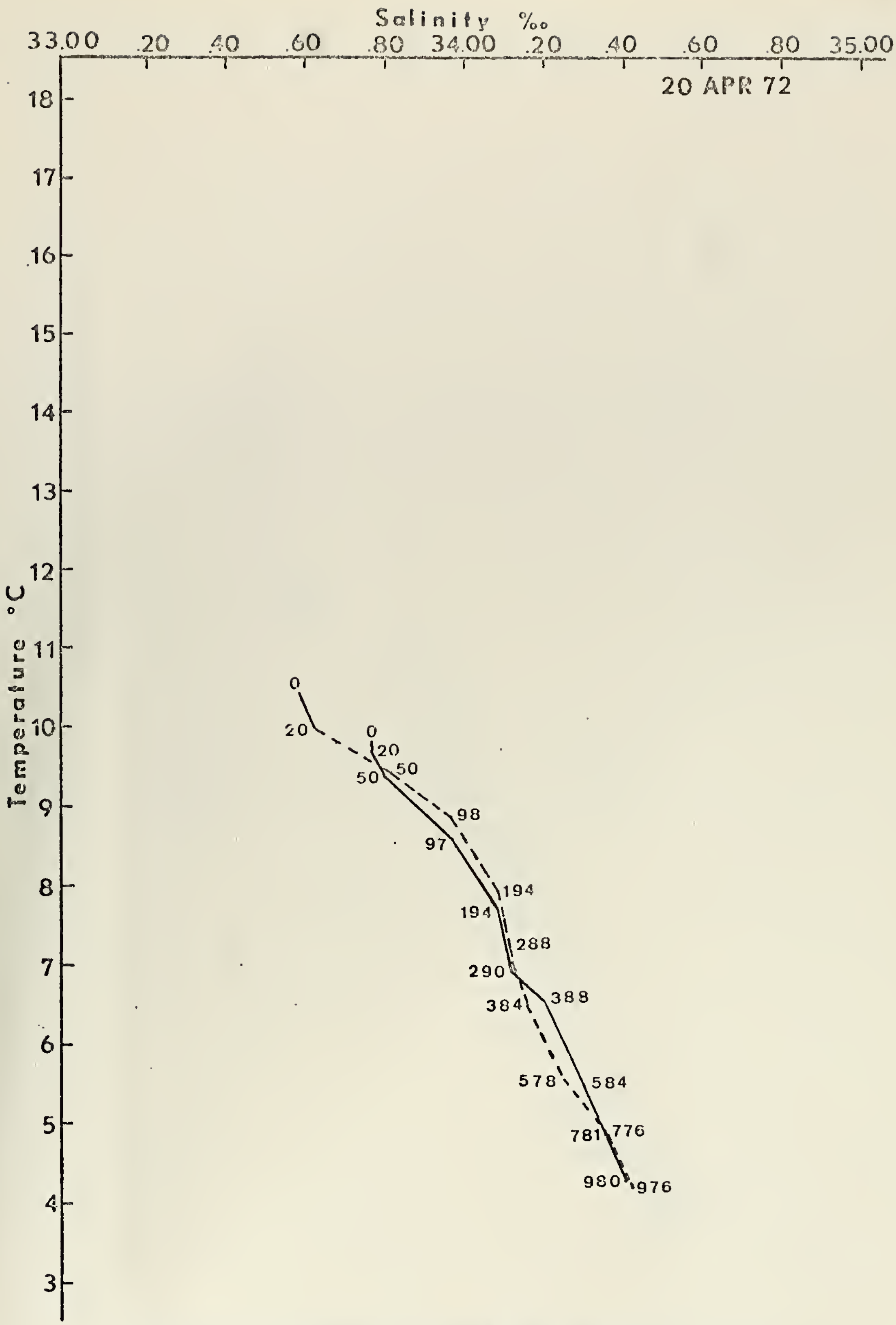


Figure 88. Typical Temperature-Salinity Curves for Stations 2 and 3 for April 1972

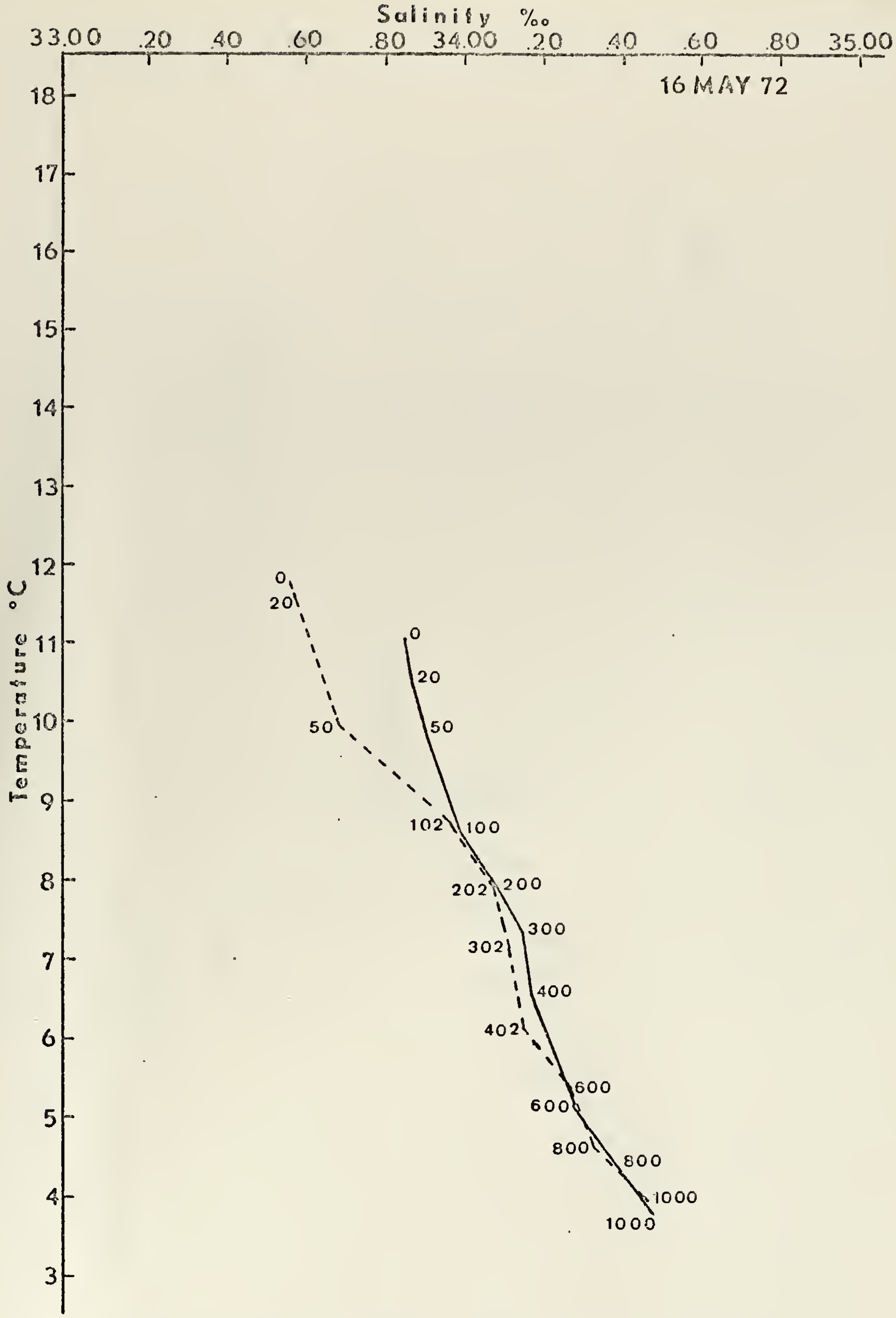


Figure 89. Typical Temperature-Salinity Curves for Stations 2 and 3 for May 1972

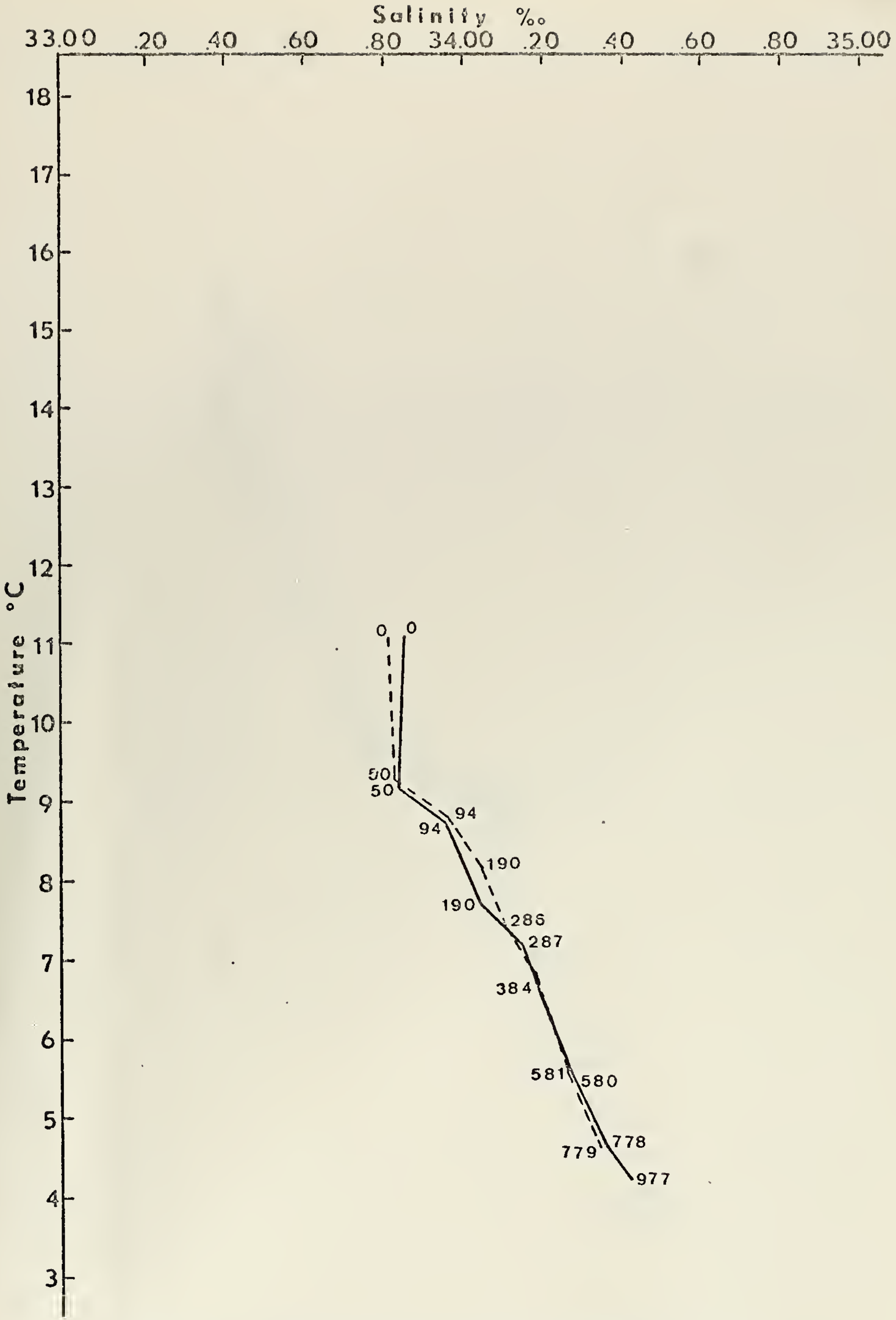


Figure 90. Typical Temperature-Salinity Curves
for Stations 2 and 3 for June 1972

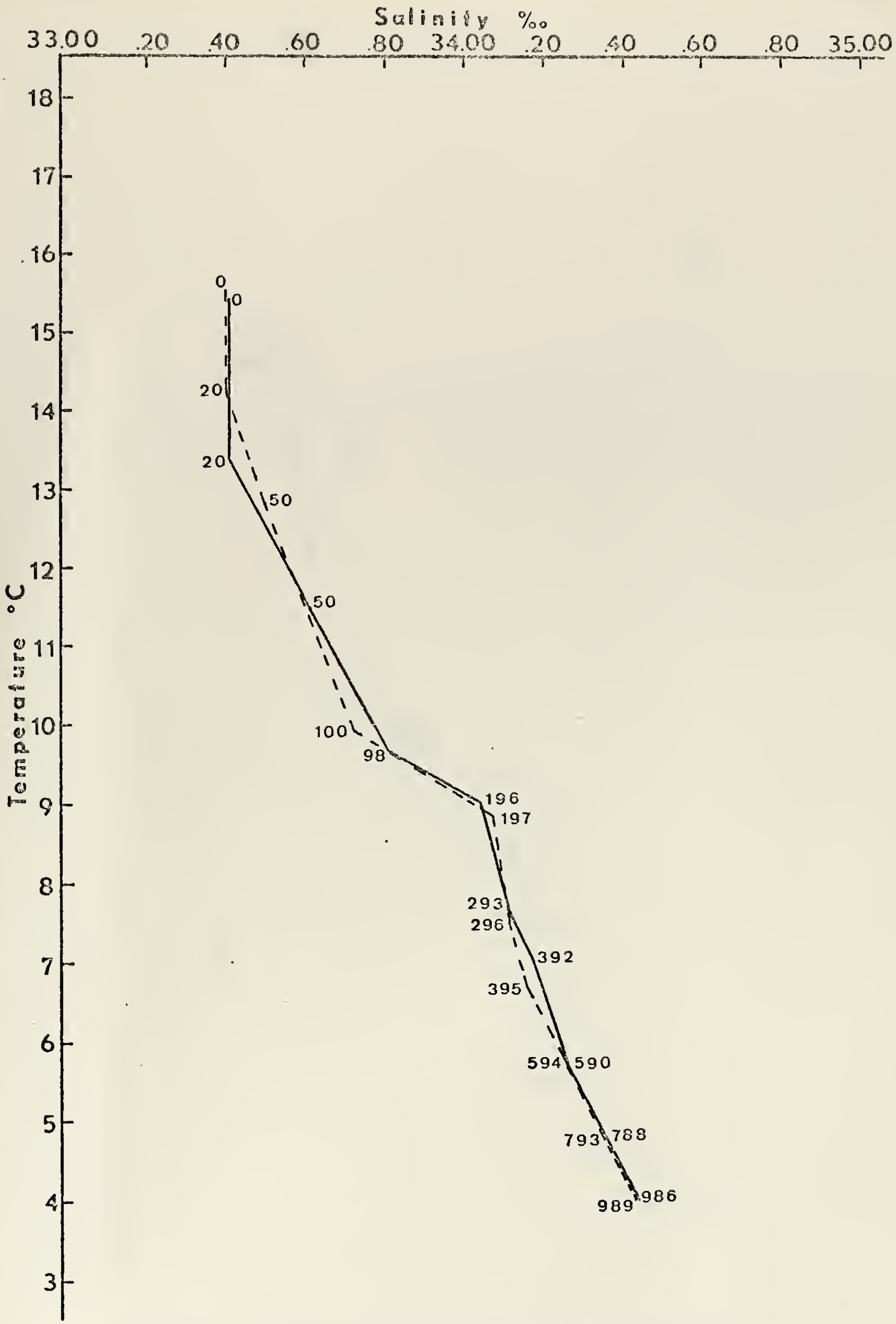


Figure 91. Typical Temperature-Salinity Curves
for Stations 2 and 3 for July 1972

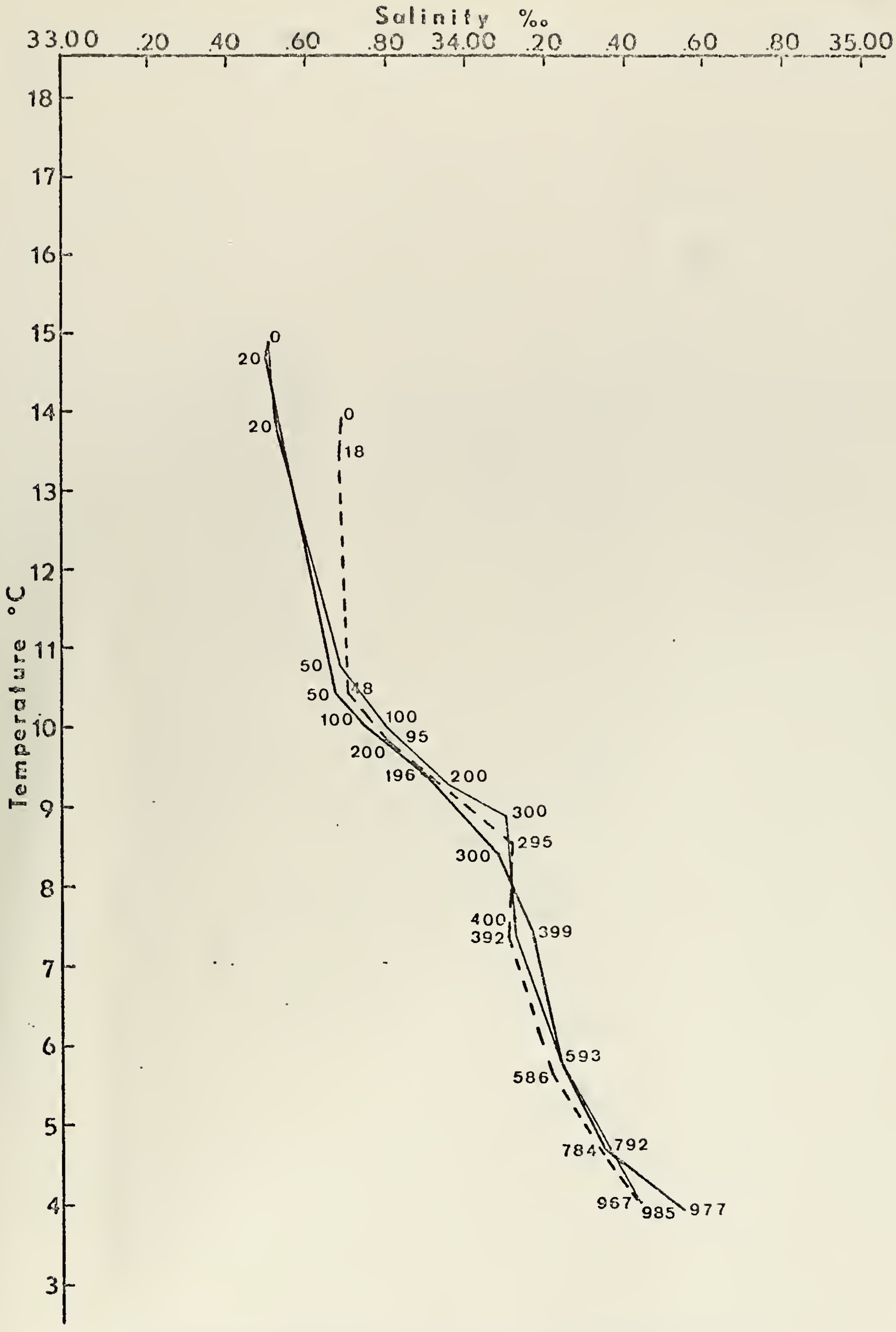


Figure 92. Typical Temperature-Salinity Curves
for Stations 2 and 3 for August 1972

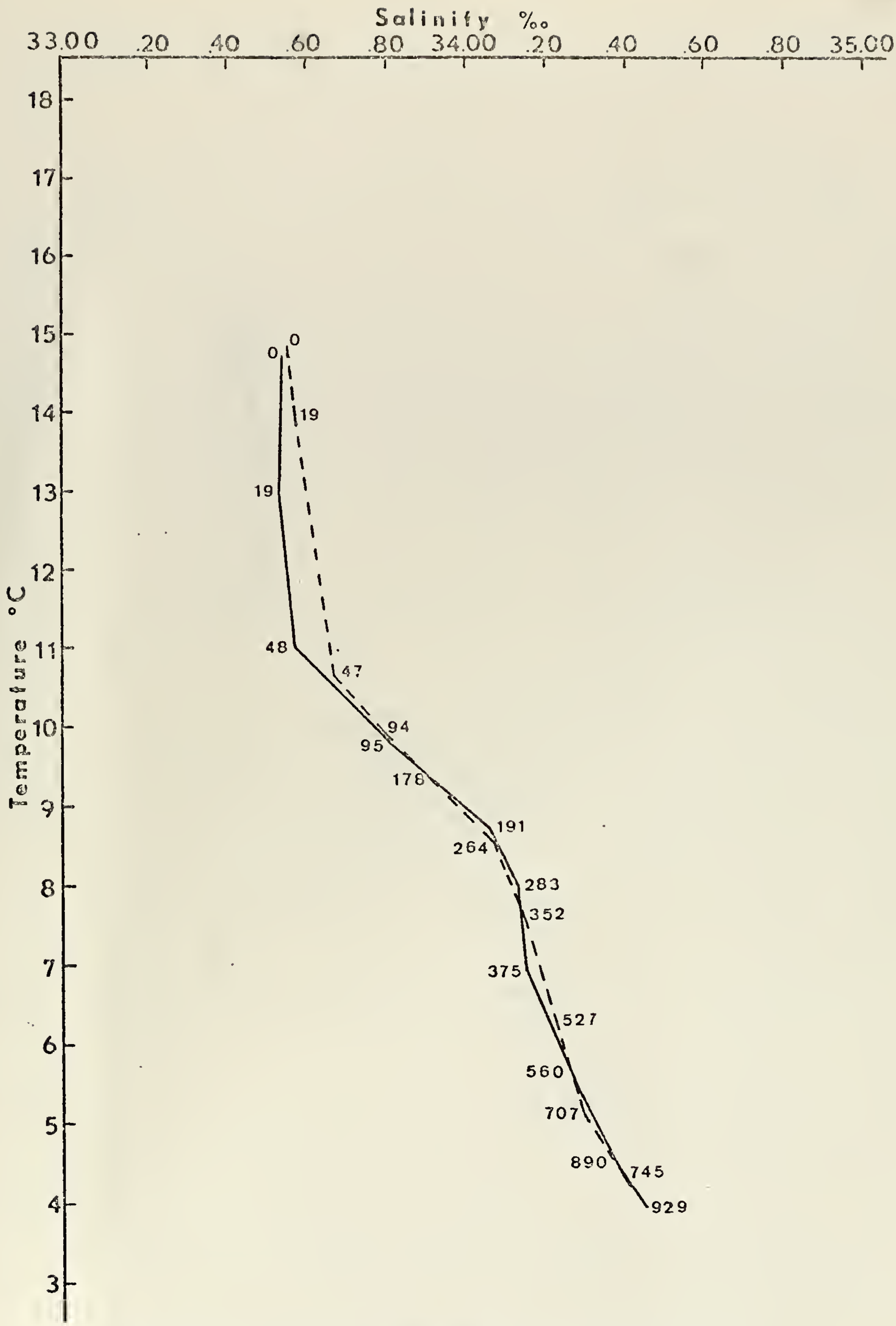


Figure 93. Typical Temperature-Salinity Curves for Stations 2 and 3 for September 1972

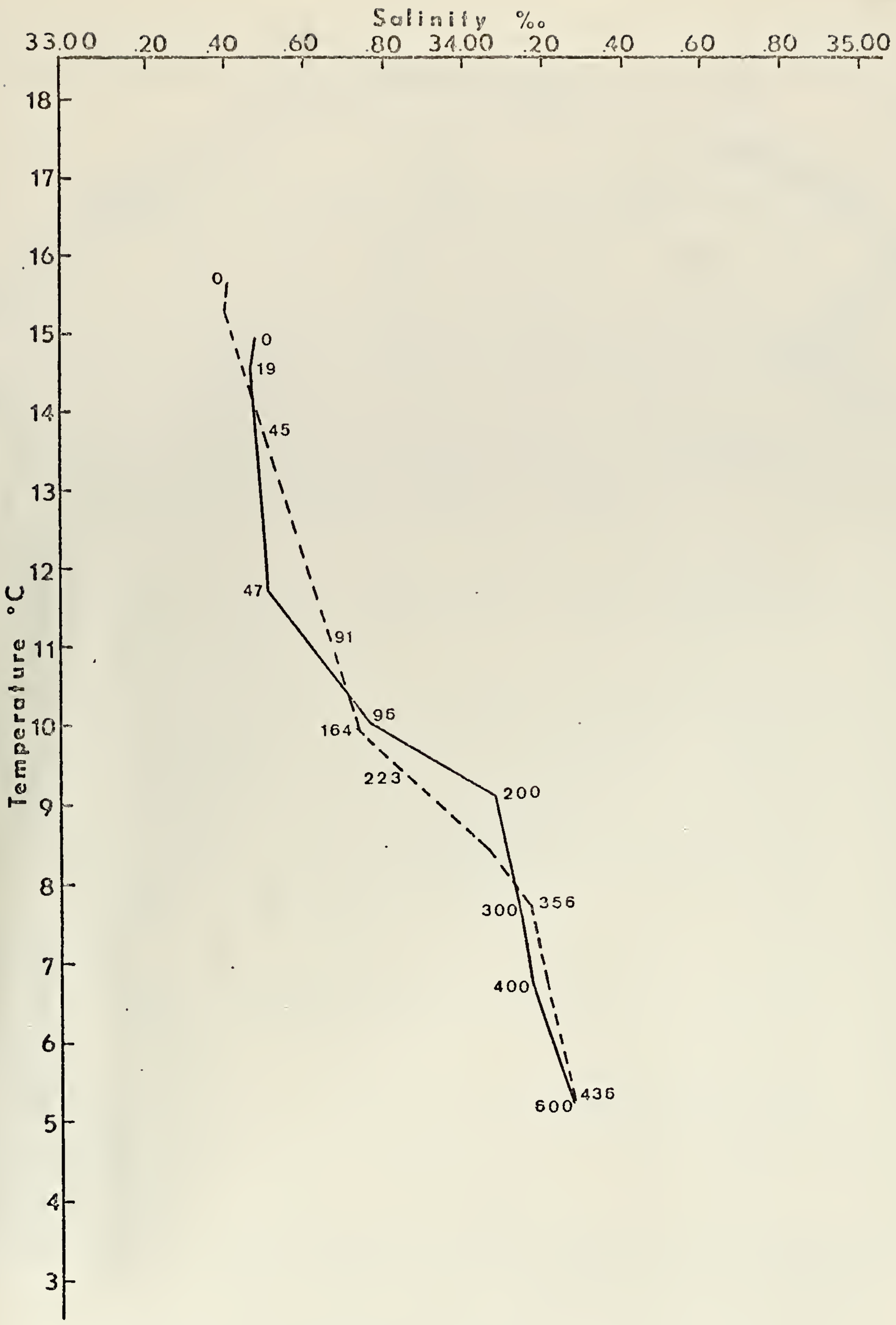


Figure 94. Typical Temperature-Salinity Curves for Stations 2 and 3 for October 1972

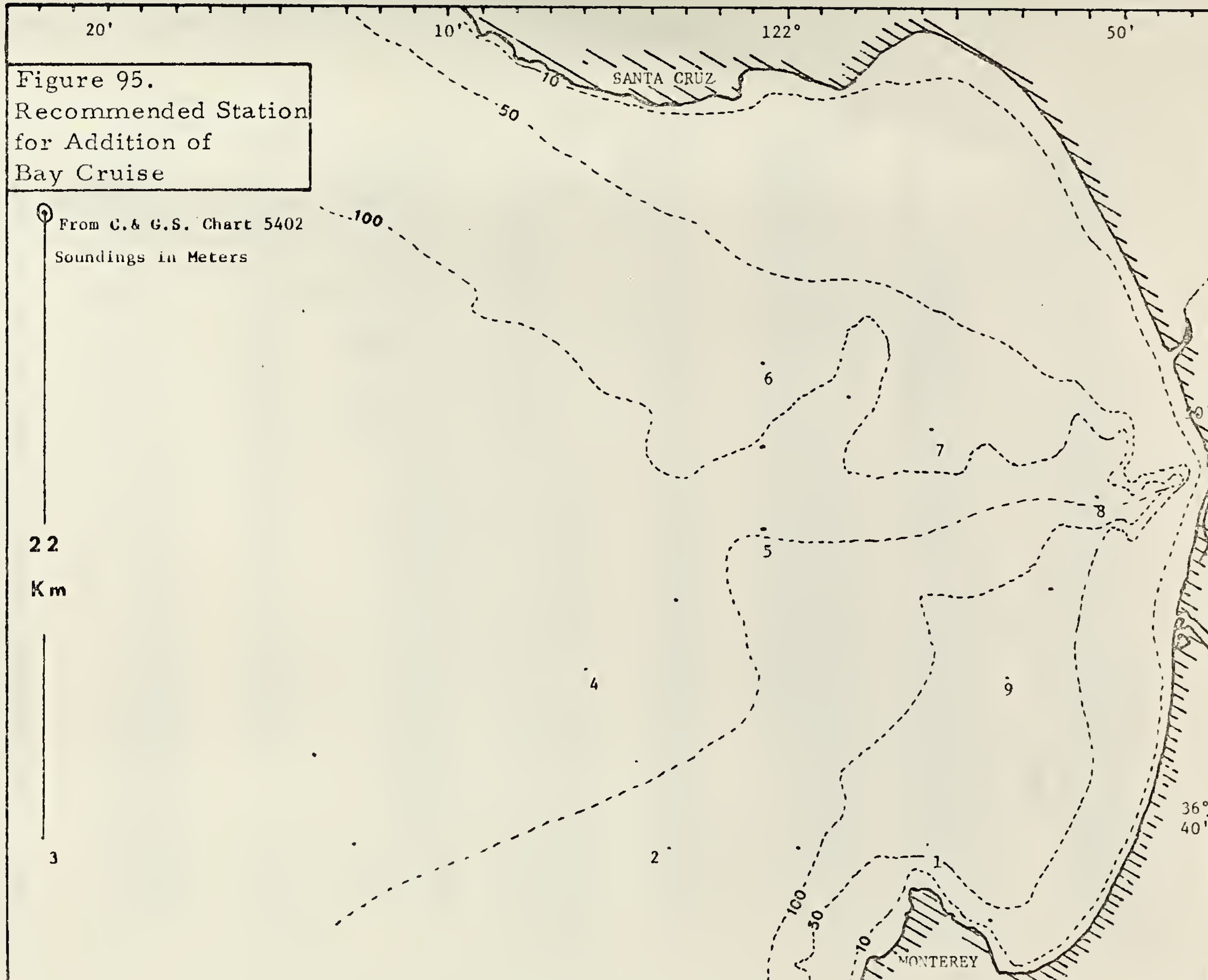


Figure 95.
Recommended Station
for Addition of
Bay Cruise

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ABSTRACT

Temperature data was obtained at nine stations in Monterey Bay on a weekly basis from September 1971 to October 1972. Monthly mean depths of the isotherms were computed and compared to the long term mean depths of these isotherms. Sea surface temperature patterns and the topographies of the 10°C surface were drawn. It was found that the period from October 1971 to May 1972 was colder than normal while the months from June 1972 to October 1972 were warmer than usual. The NMFS coastal upwelling index was a relative indicator of isotherm depth in relation to the long term mean depths of these isotherms.

Quasi-synoptic observations between two offshore stations indicated that the north-south component of the offshore current seldom exceeded 20 cm/sec. The inferred flow from the surface σ_t contours and the topographies of isothermal surfaces were compared to current flow determined by drogue measurements. The overall direction of the offshore current and the inferred flow in the bay compared reasonably well to the proposed flow in the numerical model of current patterns in the bay by Garcia [1971].

KEY WORDS	LINK A		LINK B		LINK C	
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ieostropic Currents						
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c.1 Temperature variations throughout Monterey Bay, September 1971-October 1972.